THE NATIONAL ACADEMY OF SCIENCES' DECADAL PLAN FOR AERONAUTICS

HEARINGS

BEFORE THE

SUBCOMMITTEE ON SPACE AND AERONAUTICS

COMMITTEE ON SCIENCE

HOUSE OF REPRESENTATIVES

ONE HUNDRED NINTH CONGRESS

SECOND SESSION

JULY 18, 2006 AND SEPTEMBER 26, 2006

Serial No. 109–55
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THE NATIONAL ACADEMY OF SCIENCES' DECADAL PLAN FOR AERONAUTICS: A BLUEPRINT FOR NASA?

TUESDAY, JULY 18, 2006

HOUSE OF REPRESENTATIVES,
SUBCOMMITTEE ON SPACE AND AERONAUTICS,
COMMITTEE ON SCIENCE,
Washington, DC.

The Subcommittee met, pursuant to call, at 2:06 p.m., in Room 2318 of the Rayburn House Office Building, Hon. Ken Calvert [Chairman of the Subcommittee] presiding.

COMMITTEE ON SCIENCE
SUBCOMMITTEE ON SPACE AND AERONAUTICS
U.S. HOUSE OF REPRESENTATIVES
WASHINGTON, DC 20515

Hearing on

The National Academy of Sciences' Decadal Plan for Aeronautics: A Blueprint for NASA?

July 18, 2006
2:00 p.m. – 4:00 p.m.
2318 Rayburn House Office Building

<u>WITNESS LIST</u>

Dr. Paul Kaminski
Chairman, Steering Committee
National Research Council's "Decadal Survey of Civil Aeronautics" (2006)

Dr. Steve Merrill
Study Director
National Research Council's "Aeronautics Innovation: NASA's Challenges and Opportunities"

Dr. Michael Romanowski
Vice President for Civil Aviation
Aerospace Industries Association

Dr. Parviz Moin
Professor
Mechanical Engineering
Stanford University
Director
Institute for Computational and Mathematical Engineering

HEARING CHARTER

SUBCOMMITTEE ON SPACE AND AERONAUTICS
COMMITTEE ON SCIENCE
U.S. HOUSE OF REPRESENTATIVES

The National Academy of Sciences' Decadal Plan for Aeronautics: A Blueprint for NASA?

TUESDAY, JULY 18, 2006
2:00 P.M.–4:00 P.M.
2318 RAYBURN HOUSE OFFICE BUILDING

Purpose

On Tuesday, July 18, 2006, at 2:00 p.m., the Space and Aeronautics Subcommittee will hold the first of two hearings on NASA's efforts to refocus and reshape its civil aeronautics research and development program. The hearing will take testimony from witnesses representing industry, academia, and the National Academies. At the second hearing planned for September (date TBD), Dr. Lisa Porter, NASA Associate Administrator for Aeronautics Research Mission Directorate, will testify.

Together, these hearings will review the results of two reports recently released by the National Research Council (NRC) on NASA's civil aeronautics R&D program. The first, *Aeronautics Innovation: NASA's Challenges and Opportunities,* published in early May, provides recommendations on tools, techniques, and management practices to facilitate and accelerate innovation in NASA's aeronautics programs. The second, *Decadal Survey of Civil Aeronautics,* published in early June, provides a specific set of priority projects to be undertaken in the next 10 years. Over the years, similar surveys in NASA's science programs have been a significant factor in setting program and budget priorities. The aeronautics decadal survey is the first time such a comprehensive survey has been done on aeronautics.

The hearings will also help set the stage for the development of an overarching national aeronautics policy, due to be released at the end of this year. Congress directed the Administration, in last year's NASA Authorization bill, to develop a national aeronautics policy to guide federal investments in aeronautics research because of concerns over the downward trend over the last decade in funding for NASA's aeronautics program and the changing goals and priorities.

Witnesses

Dr. Paul Kaminski is Chairman of the National Research Council's Steering Committee that produced the *Decadal Survey of Civil Aeronautics* (released in June 2006). He is the Chairman and CEO of Technovation, Inc. and served as the Under Secretary of Defense for Acquisition and Technology in the Clinton Administration.

Dr. Steven Merrill is Executive Director of the National Research Council's Board on Science, Technology, and Economic Policy. He managed the NRC Committee that produced *Aeronautics Innovation: NASA's Challenges and Opportunities* (released in May 2006).

Dr. Michael Romanowski is Vice President for Civil Aviation, Aerospace Industries Association.

Dr. Parviz Moin is a Professor of Mechanical Engineering at Stanford University and Director of the Institute for Computational and Mathematical Engineering, the Center for Turbulence Research, and the ASCI Center for Integrated Turbulence Simulations. He is a fellow of the American Physical Society.

Overarching Questions

1. What should the goals, strategies and activities be for NASA's aeronautics research and development program?
2. What should NASA be doing to ensure that its research is relevant to the long-term needs of industry and is used by industry? What should NASA be

doing to help keep the academic research enterprise healthy and to ensure an adequate supply of aeronautics engineers and researchers?

Reshaping NASA's Aeronautics Research Program

Early this year Dr. Lisa Porter, who was appointed as NASA's Associate Administrator for Aeronautics Research Mission Directorate (ARMD) in October 2005, announced a major restructuring of the aeronautics research program. The new goals are to re-establish ARMD's core competencies in subsonic, supersonic and hypersonic flight; to focus research in areas that are appropriate to ARMD's unique capabilities; and to directly address the fundamental research needs of the Next Generation Air Transportation System (NGATS), a partnership with the Federal Aviation Administration (FAA) and other agencies. Dr. Porter's "back-to-basics" approach puts greater emphasis on fundamental research and less emphasis on technology demonstrations.

Prior to Dr. Porter's arrival, ARMD had three major programs: Vehicle Systems; Aviation Safety and Security; and Airspace Systems. Vehicle Systems was the largest and included plans to pursue four major technology demonstration flight projects: subsonic noise reduction; sonic boom reduction; zero emissions aircraft; and a high-altitude, long-endurance unmanned air vehicle. All the demonstration projects have been canceled.

Following the restructuring, Vehicle Systems was renamed Fundamental Aeronautics; Aviation Safety and Security was renamed Aviation Safety; and Airspace Systems remained unchanged. A fourth program line, Aeronautics Test Program, was established to ensure long-term stewardship of eleven NASA aeronautics test facilities (wind tunnels and engine test stands) located at the Ames Research Center, Langley Research Center, and Glenn Research Center, which are considered to be critical national assets.

National Research Council Reports

Aeronautics Innovation: NASA's Challenges and Opportunities

In mid-2004, NASA asked the National Academies' Board on Science, Technology, and Economic Policy (STEP) to recommend tools, techniques, and practices that might facilitate and accelerate innovation in NASA's aeronautics research program. To carry out this task, the NRC created an ad hoc committee—known as the Committee on Innovation Models for Aeronautics Technologies—of academic experts in technology management and public administration.

In carrying out their task, the committee said it was struck by the growing discrepancy between the goals and objectives of NASA's aeronautics research program and the resources available to it. While the committee developed a roster of recommendations to improve management practices, it clearly indicated that the first order of business should be to bridge the gap between the stated goals and budget realities. Specifically, the report said:

> The committee concluded that NASA's aeronautics program faces an overriding management challenge: a lack of national consensus about the Federal Government's role in civilian aviation generally and NASA's role in aviation technology development in particular. On the one hand, the community of industry, academic, and other stakeholders and experts support an expansive public research and development program with NASA playing a lead role. On the other hand, successive administrations and sessions of Congress have over the past seven or eight years reduced NASA's aeronautics budget without articulating how the program should be scaled back. In these circumstances, NASA has tried to maintain an expansive program by spreading diminishing resources across existing research establishments and many objectives and projects—too many to ensure their effectiveness and the application of their results.

The committee made numerous recommendations, summarized below, regarding technology transition planning, and personnel and financial management practices, to improve innovation in the program. Some of the recommendations, such as establishing a national aeronautics policy, were already in progress at the time the report was released.

Summary of Key Recommendations:

- Congress and the Executive Branch should engage in a dialogue on the goals for civil aviation (i.e., establish a national aeronautics policy).
- NASA must translate the national aeronautics policy into a balanced portfolio of programs that are in alignment with its resources.

- NASA should set decision criteria to evaluate progress and force accountability to all involved.
- NASA should cultivate close relationships and regularly involve external partners in all phases of an activity, including technology transition (hand-off).
- NASA should work aggressively to solidify its reputation as a trustworthy, reliable partner.
- NASA should implement more flexible personnel policies to increase collaboration and innovative thinking.
- NASA should expand the use of prizes to offer high-profile aeronautics prizes to generate increased participation and public interest.
- NASA should modify full-cost pricing policies for use of facilities, with costs more closely aligned with marginal costs.
- NASA should explore the use of working capital fund structures, such as used in the Defense Department, as well as funding pools and contingency accounts to provide stability and flexibility.

A complete set of the report's recommendations appears in the Appendix. A full copy of the report appears at the website: *http://darwin.nap.edu/books/0309101883/html*

Decadal Survey of Civil Aeronautics: Foundation for the Future

In 2005, NASA contracted with the NRC, under the auspices of the its Aeronautics and Space Engineering Board (ASEB), to develop a consensus document representing the external (industry and academia) community's views about what NASA's aeronautics research priorities ought to be. The effort was led by a Steering Committee chaired by Dr. Paul Kaminski and had five panels, (Aerodynamics and Aeroacoustics; Propulsion and Power; Materials and Structures; Dynamics, Navigation and Control, and Avionics; and Intelligent and Autonomous Systems), that drew on a group of 85 aeronautics experts from academia and industry. This was the first decadal survey ever produced for NASA's aeronautics program.[1] Their report was released on June 5, 2006. A copy of their recommendations appears in the Appendix; a copy of the full report can be found at: *http://www.nap.edu/catalog/11664.html*

Decadal surveys are designed to provide strategic guidance to NASA. With respect to the space sciences programs, NASA has over the years relied heavily on survey recommendations to shape the scope, content and timing of NASA's missions.

The report lays out five key areas for research: aerodynamics and aeroacoustics; propulsion and power; materials and structures; dynamics, navigation and control, and avionics; and intelligent and autonomous systems, operations and decision-making, human integrated systems, networking and communications. Under each of those areas, the report lays out a prioritized list of "challenges" to address—51 in all. The report also lays out five "themes" that cut across all the research areas.

Summary of Key Recommendations (complete list is in the Appendix):

- NASA should use the 51 Challenges as the foundation for its aeronautics research program over the next decade.
- A high priority should be placed on establishing and maintaining a stable aeronautics research program.
- NASA should use the five Common Themes (see Appendix for details) to make the most efficient use of research funding.
- NASA should support research to develop practical certification standards for new technologies.
- The U.S. Government should align organizations and develop techniques to improve change management to assure a safe and cost-effective transition to the air transportation system of the future.
- NASA should ensure that it involves universities and industry in its planning, and develop a more balanced funding allocation between "in-house" and external organizations.
- NASA should consult with non-NASA stakeholders, such as in the Defense Department and FAA, on the most effective use of facilities and tools applicable to aeronautics research.

[1] The NRC has written decadal surveys for NASA's space sciences programs for more than 50 years. As the name implies, these studies are expected to be updated every ten years.

- The U.S. Government should conduct a high-level review of organizational options for ensuring U.S. leadership in civil aeronautics.

Key Issues

What goals for aeronautics research are realistic given the projected budget? For the last several years NASA's budget for the Aeronautics Research Mission Directorate (ARMD) has been declining both in dollars, and as a fraction of NASA's overall budget. Specifically, in FY04 NASA's budget for aeronautics was over $1 billion. NASA's aeronautics budget for FY06 was $884 million, and NASA's request for FY07 is $724 million. (The House-passed appropriation for FY07 provides an additional $100 million above that.) If this year's request is enacted, NASA's aeronautics budget will have sustained a 32 percent cut in three years, even though NASA's budget as a whole will have increased by nine percent over the same period. While ARMD's budget is projected to be flat over the next five years, it's burdened with a disproportionate share of infrastructure costs (e.g., wind tunnels and test stands). At issue is how many of the Decadal Survey's recommendations can NASA realistically accomplish? What is the appropriate balance between goals and budget?

Does NASA's research portfolio strike the right balance between basic research and work that may be of more direct and immediate relevance to industry? In the past year, NASA has reoriented its portfolio more toward fundamental research, arguing that that is an appropriate federal role and that the results of such research will increase knowledge in a way that will allow significant advances in aviation. But the NRC's Aeronautics Innovation study argued that NASA should pursue a limited number of research projects to a high enough technology maturity level so that industry would be willing to adopt the technology. Otherwise, it said, NASA may in time lose its relevance to industry.

Should NASA implement the priorities of the Decadal Survey of Civil Aeronautics? NASA is still putting together specific project plans to carry out its research agenda. The Decadal Survey provides technical objectives and milestones for each of the 51 "Challenges," but without a similar level of detail on NASA's plans it is difficult to compare the two. One point of the hearing, and the follow-up hearing with NASA in the fall, will be to get both NASA and the Academy panel to provide more details and an assessment of their respective research agendas so they can be compared and evaluated.

Has NASA struck the appropriate balance between in-house work and external work? The NRC Decadal Survey states that NASA must create a more balanced split in the allocation of funding between in-house research performed by NASA engineers and external research performed by industry and academia. NASA's budget documents appear to allocate 93 percent of funds for in-house work and seven percent for external work. However, NASA argues this breakout is closer to 75 percent in-house and 25 percent external. This is because NASA's numbers include funds for service contracts that are not focused on research.

FY07 Aeronautics Budget Highlights

For FY06, ARMD's appropriated budget is $884.1 million. NASA is proposing in FY07 to spend $724.4 million on aeronautics, a cut of $160 million from this year (an 18 percent reduction).

ARMD's four programs are listed in the table below. Airspace Systems supports the Joint Planning and Development Office's (JPDO) efforts to develop and deploy the Next Generation Air Transportation System (NGATS). (The Subcommittee held a hearing on the JPDO earlier this year.) The Aeronautics Test Program is new for FY07 and pays a portion of maintenance and operational costs for 11 nationally important wind-tunnel test facilities owned by NASA.

FY07 NASA Aeronautics Funding Request ($=millions)

	FY04 Actual	FY05 Actual	FY06 Actual	FY07 Budget	FY08 Runout	FY09 Runout	FY10 Runout	FY11 Runout
Aviation Safety	183.1	183.0	148.4	102.2	102.1	116.1	119.9	119.8
Airspace Systems	232.3	148.8	173.9	120.0	124.0	105.4	91.1	89.4
Fundamental Aeronautics	641.4	630.2	561.7	447.2	449.3	452.9	452.5	452.8
Aeronautics Test Program				55.0	56.4	58.0	59.2	60.7
TOTAL	**$1056.8**	**$962.0**	**$884.0**	**$724.4**	**$731.8**	**$732.4**	**$722.7**	**$722.7**
ARMD share of agency budget (%)	**6.9%**	**5.7%**	**5.3%**	**4.3%**	**4.2%**	**4.2%**	**4.0%**	**3.9%**

ARMD carries a disproportionate share of the agency's personnel and infrastructure costs, largely due to the agency's investment in test facilities at NASA's three aeronautics research centers: Langley Research Center (VA); Glenn Research Center (OH); and Dryden Flight Research Center (CA). In addition, ARMD employs 23 percent of the agency's workforce.

Aviation Safety

Prior to the reorganization early this year, this program was called "Aviation Safety and Security." NASA determined that security issues were not its responsibility (it resides within the Department of Homeland Security), thus that portion of its research portfolio has been transferred or dropped.

The Aviation Safety program's goal is improving the safety of current and future aircraft operating in our nation's airspace. The research focus is on the way aircraft are designed, built, operated, and maintained. Projects include Integrated Vehicle Health Management; Integrated Intelligent Flight Deck; Integrated Resilient Aircraft Control; and Aircraft Aging and Durability. For FY07, ARMD is proposing to spend $102 million, a 31 percent reduction compared to this year's $148 million appropriation.

Airspace Systems

The goal of the Airspace Systems program is to research and develop tools and operational concepts to make our nation's Air Traffic Management system safer, more efficient and secure, and capable of handling larger numbers of aircraft. Airspace Systems performs long-term R&D research for the Federal Aviation Administration. Following creation of the JPDO—as required by Congress in the *Vision 100* legislation, now Public Law 108–176—Airspace Systems was aligned to support the work of the JPDO to design and deploy the Next Generation Air Transportation System. For FY07, ARMD is proposing to spend $120 million, a 31 percent reduction compared to this year's $174 million appropriation.

Fundamental Aeronautics

For FY07 NASA proposed a reorganization, a reduction in funding, restoration of hypersonics and rotorcraft research, and a renaming of the program. ARMD is proposing to spend $447.2 million, a 20 percent reduction compared to this year's $561.7 million appropriation.

The goal of Fundamental Aeronautics is to provide long-term investment in research to support and sustain expert competency in core areas of aeronautics technology. Four research thrusts have been established: Hypersonics; Subsonic—Rotary Wing; Subsonic—Fixed Wing; and Supersonics. To achieve these goals, ARMD plans to focus on advanced tools such as new computational- and physics-based software modeling and simulation programs and capabilities that will enable whole new classes of aircraft that not only meet the noise and emissions requirements of the future, but also provide fast and efficient flight.

Aeronautics Test Program

The Aeronautics Test Program (ATP) is new and part of a larger NASA program called Shared Capabilities Asset Program (S–CAP). ATP's purpose is to ensure the strategic availability of a minimum, critical suite of wind tunnels/ground test facilities which are necessary to meet the mission of ARMD, NASA, and national needs.

ATP funds a portion of the fixed operating costs of eleven wind tunnels/ground test facilities at Ames Research Center, Langley Research Center, and Glenn Research Center.

The RAND Corporation conducted a study for NASA that recommended that NASA ensure the continued operation of 29 of its 31 wind tunnels. RAND estimated the annual operating cost of all 31 tunnels to be $125–$130 million and concluded that while some of the tunnels were not being utilized at a high rate, they offered capabilities that could be needed in the future and would be hard to replicate if shut down. ATP is NASA's response to these concerns.

Last year's NASA Authorization bill included a provision directing the Office of Science and Technology Policy to report to Congress on the Nation's long-term strategic needs for aeronautics test facilities. It also bars NASA from closing any of its test facilities until the report is delivered, and requires the NASA Administrator to certify to Congress that proposed closures will have no adverse impact. The report has not yet been delivered.

For FY07, NASA is proposing a budget of $55 million for ATP. This figure does not represent all of NASA's investment in wind tunnels/ground test facilities, but only for 11 tunnels deemed to be under-utilized and of critical national importance.

National Aeronautics Policy

The NASA Authorization Bill included a provision directing the President to develop a national policy to guide federal aeronautics research and development through 2020. The bill specified that the policy include national goals for aeronautics R&D and describe the roles and responsibilities for each federal agency that will carry it out. The policy is due at the end of this calendar year.

NASA and the White House Office of Science and Technology Policy, working through the National Science and Technology Council, are leading the policy's development.

Background

NASA's Aeronautics Research

NASA's roots in aeronautics research reach back almost 90 years—to 1917—when the National Advisory Committee on Aeronautics was formed. Responding to the launch of Sputnik almost 40 years later, in 1958 Congress passed legislation changing the agency's name to the National Aeronautics and Space Administration and broadening its mission to include human space flight and space exploration.

NASA-developed technology is found in virtually every airplane flying today. Examples include the high-bypass turbine engine that provides much greater fuel efficiency and lower noise emissions than original 1960's-era jet engines; "fly-by-wire" control systems that use computers and wires instead of heavy, maintenance-intensive hydraulics systems to control an airplane's rudder and wing flaps; flight management systems such as the "black boxes" that continuously monitor an aircraft's engines, speed, location, and other critical parameters; and advanced composites made out of materials such as graphite and epoxy that can be used to replace heavier and more maintenance-intensive aluminum alloy structures. The Boeing 787, now under development, will be the first large civil aircraft to use composite materials in its fuselage.

The U.S. Aircraft Industry

The domestic aeronautics industry has changed substantially over the last ten to fifteen years through consolidations. Today there is only one manufacturer of large civil aircraft, Boeing, and just two turbine engine manufacturers for large civil aircraft, General Electric and Pratt & Whitney. The U.S. has no domestic regional jet manufacturers, the fastest growing segment in civil aviation; most are made in Canada and Brazil. The business jet and general aviation aircraft industry have a good number of domestic producers.

Boeing is this country's largest exporter of manufactured products (based on dollar value), and draws on thousands of suppliers whose products are found in each jet. Airbus,[2] a European company, had overtaken Boeing in sales earlier this decade, but Boeing has since regained the lead, and Airbus has fallen behind schedule in producing its new A380 aircraft, a "super jumbo" that would be the world's largest passenger-carrying aircraft (it can seat over 800 in a single-class layout). The A380's first commercial delivery is now scheduled for late this year.

[2] Airbus began over 30 years ago as a government-created and owned entity with direct investment by the British, French, Spanish, and German governments. It has since been spun off as a private company owned by EADS and BAE systems, both European based conglomerates.

Earlier this decade, the European Union (EU) identified aeronautics as part of a continent-wide industrial strategy. The EU produced a research program document, *"Aeronautics 2020,"* that explicitly stated the objective of having Europe become the world's leading supplier of aeronautics goods and services and achieving parity with Boeing. The EU also has set a goal of taking a leadership role designing and producing the next generation air traffic management services.

National Institute of Aerospace

In April 2005, the National Institute of Aerospace[3] produced a report titled *Responding to the Call: Aviation Plan for American Leadership* that included an exhaustive list of research projects and activities that should be pursued by NASA if our government were intent on revitalizing the capabilities and products of the U.S. aerospace industry. The report recommended that ARMD's budget be *increased* by an average of $885 million over each of the next five years to support their research agenda. A copy of the full report can be found at: *http://www.nianet.org/nianews/AviationPlan.php*

Witness Questions

In their letters of invitation, the witnesses were asked to address the following questions:

Dr. Paul Kaminski, National Research Council (ASEB)

Please briefly describe the results of the Decadal Survey and answer the following questions:

1. How would you assess the Aeronautics Research Mission Directorate's (ARMD) program goals and strategies? Given the resources currently allocated to it, is ARMD properly structured, and is it pursuing the right lines of research? Is the balance between in-house and out-of-house research appropriate?
2. Of the 51 research and technology challenges identified in the report, what do you consider to be the top three and why?

Dr. Steven Merrill, National Research Council (STEP)

Please briefly describe the conclusions and recommendations of your report and address the following questions:

1. How would you assess the Aeronautics Research Mission Directorate's (ARMD) program goals and strategies? Is NASA's emphasis on foundational research appropriate? Given the resources currently allocated to it, is ARMD properly structured, and is it pursuing the right lines of research?
2. In a constrained budget environment, how should NASA best balance: (1) research conducted in-house versus contracting with outside entities; and (2) near-term research versus research for long-term, high-risk technologies? How can NASA preserve a federal cadre of aeronautics experts and capabilities while also collaborating with academia and industry?

Dr. Michael Romanowski, Vice President, Aerospace Industries Association

1. How would you assess the Aeronautics Research Mission Directorate's program goals and strategies? Is NASA's emphasis on foundational research appropriate? Given the resources currently allocated to it, is ARMD properly structured, and is it pursuing the right lines of research?
2. What should NASA be doing to ensure that its research is relevant to the long-term needs of industry and is used by industry? What should NASA be doing to help keep the academic research enterprise healthy and to ensure an adequate supply of aeronautics engineers and researchers?
3. What is your reaction to the conclusions and recommendations of the Decadal Survey?

Dr. Parviz Moin, Professor of Mechanical Engineering, Stanford University

1. How would you assess the Aeronautics Research Mission Directorate's (ARMD) program goals and strategies? Is NASA's emphasis on foundational

[3] The National Institute of Aerospace is a non-profit research and graduate education institute created to conduct leading-edge aerospace and atmospheric research. It was formed by a consortium of research universities and is located at the Langley Research Center.

research appropriate? Given the resources currently allocated to it, is ARMD properly structured, and is it pursuing the right lines of research?

2. What are the major technological and competitive challenges facing the civil aeronautics industry over the next ten to fifteen years, and how well does the Aeronautics Research Mission Directorate's program attempt to address them?
3. What advantages can be gained by having NASA increase its emphasis on computational- and physics-based modeling? Why should NASA be pursuing this technology? Does NASA have the workforce and facilities to conduct this research?
4. What has been the experience, of late, with respect universities recruiting students into post-graduate aeronautics-related research programs?

Appendix A

Aeronautics Innovation: NASA's Challenges and Opportunities

NATIONAL RESEARCH COUNCIL—BOARD ON SCIENCE, TECHNOLOGY, AND ECONOMIC POLICY

PUBLISHED MAY 2006

Report Website: *http://darwin.nap.edu/books/0309101883/html*

Recommendations

Recommendation 1: Congress and the executive branch should engage in a dialogue to articulate national goals in civil aviation and the corresponding public sector roles. The government's role is likely to differ among (1) pursuit of fundamental understanding and yielding scientific and engineering results available to all; (2) pursuit of quasi-public goods such as safety, efficient management, and environmental enhancements; (3) development of improved commercial and general aviation aircraft that are successful in domestic and international markets; and (4) development of advanced aeronautics technologies for which there are currently no providers in prospect. The traditional market failure rationale for government intervention varies considerably among these categories and even within a category over time (depending, for example, on the degree of private competition).

Recommendation 2: ARMD's first order of business in promoting aeronautics innovation is to translate a national aeronautics policy into a strategic or mission focus that is in better alignment with the resources available to it—its budget, its personnel, and its technical capabilities. This, in turn, should lead to a prioritization of programs and projects involving the research centers, external grantees, and contractors. Clearly, the result may be a reduced mission scope and portfolio but one with greater impact on innovation in air transportation.

Recommendation 3–A: Conceive of R&D activities as a cohesive and strategically balanced portfolio of projects and competencies closely aligned with mission and stakeholder needs.

Recommendation 3–B: Graphical illustrations of the portfolio are particularly useful tools for fostering communication and discussion and identifying and resolving disagreements, both internally among managers and in engaging external stakeholders and customers.

Recommendation 3–C: Use decision processes, sometimes referred to as decision gate processes, at predetermined points to establish common expectations among customers, leaders, and the technical team throughout the development process, to clarify goals, schedules, deliverables, concrete target performance metrics, and review templates and to set decision criteria and force accountability of all constituents involved.

Recommendation 3–D: Pursue a portfolio "balanced between near-term needs, driven by market forces, and longer-term investments required to achieve transformational national capabilities."

Recommendation 3–E: NASA should continue to undertake core competency reviews and explicitly include aeronautics among the highest priority core competencies. Within aeronautics, the ranking of competencies should take into account world leadership in technology, public additive value, and skills enabling partnerships and transitioning processes.

Recommendation 4–A: ARMD should implement and explicitly regularize for all projects organization-wide series of management tools aimed at fostering technology transition to users.

Recommendation 4–B: ARMD should cultivate close relationships with external partners, engaging them very early in jointly conceptualizing, planning, and prioritizing all R&D activities and sustaining regular involvement through the implementation phase.

Recommendation 4–C: ARMD should work aggressively to solidify its reputation as a trustworthy, reliable partner.

Recommendation 4–D: JPDO may be a model for future ARMD technology management decision-making through close external collaboration, with joint recommendations guiding ARMD portfolio planning.

Recommendation 4–E: Documented planning for technology transition (hand-off) to external stakeholders should be a universal managerial practice for all ARMD R&D projects and integral to the portfolio planning and prioritizing process.

Recommendation 4–F: The variety of technologies and the diversity of stakeholder capabilities require increased ARMD flexibility and variability with regard to project time horizons and technology readiness levels.

Recommendation 5–A: ARMD should implement more flexible personnel practices, increase incentives for creativity, and actively manage existing constraints on staffing decision-making to minimize their innovation-inhibiting effects.

Recommendation 5–B: ARMD should increase rotation and seconding of personnel to and from its several research centers and its external partners as tools for enhancing staffing and competency flexibility, fostering the early engagement of partners, and facilitating technology transfer.

Recommendation 5–C: NASA should foster external customer contact early in and throughout the careers of ARMD technical personnel.

Recommendation 5–D: ARMD should pilot test a dual track, pay-for-performance program similar to that in place at the Air Force Research Laboratory.

Recommendation 5–E: ARMD should allow R&D personnel some fraction of their time for free thinking and encourage its use by organizing regular employee idea fairs that attract external stakeholders.

Recommendation 5–F: NASA should expand its Centennial Challenges program to offer high-profile aeronautics prizes of a magnitude sufficient to generate considerable participation and public attention.

Recommendation 6–A: NASA should modify full-cost pricing for ARMD facilities use, with charges more closely aligned with marginal costs.

Recommendation 6–B: ARMD should work with OMB and Congress to establish separate centrally funded budget lines for national infrastructure and facilities management.

Recommendation 6–C: Because midstream changes are the nature of leading edge R&D, ARMD should achieve greater budget and milestone flexibility through centrally funded pools and contingency accounts.

Recommendation 6–D: ARMD should explore establishing Working Capital Fund structures for wind tunnels and aeronautics R&D services.

Recommendation 6–E: ARMD should negotiate with congressional sponsors and earmark recipients to align mandated activities better with established programs and should assign the projects to a separate budget account and management area.

TABLE ES-1 Fifty-one Highest Priority Research and Technology Challenges for NASA Aeronautics, Prioritized by R&T Area

A Aerodynamics and Aeroacoustics	B Propulsion and Power	C Materials and Structures	D Dynamics, Navigation, and Control, and Avionics	E Intelligent and Autonomous Systems, Operations and Decision Making, Human Integrated Systems, Networking and Communications
A1 Integrated system performance through novel propulsion-airframe integration A2 Aerodynamic performance improvement through transition, boundary layer, and separation control A3 Novel aerodynamic configurations that enable high performance and/or flexible multi-mission aircraft A4a Aerodynamic designs and flow control schemes to reduce aircraft and rotor noise A4b Accuracy of prediction of aerodynamic performance of complex 3D configurations, including improved boundary layer transition and turbulence models and associated design tools A6 Aerodynamics robust to atmospheric disturbances and adverse weather conditions, including icing A7a Aerodynamic configurations to leverage advantages of formation flying A7b Accuracy of wake vortex prediction, and vortex detection and mitigation techniques A9 Aerodynamic performance for V/STOL and ESTOL, including adequate control power A10 Techniques for reducing/mitigating sonic boom through novel aircraft shaping A11 Robust and efficient multidisciplinary design tools	B1a Quiet propulsion systems B1b Ultraclean gas turbine combustors to reduce gaseous and particulate emissions in all flight segments B3 Intelligent engines and mechanical power systems capable of self-diagnosis and reconfiguration between shop visits B4 Improved propulsion system fuel economy B5 Propulsion systems for short takeoff and vertical lift B6a Variable-cycle engines to expand the operating envelope B6b Integrated power and thermal management systems B8 Propulsion systems for supersonic flight B9 High-reliability, high-performance, and high-power-density aircraft electric power systems B10 Combined-cycle hypersonic propulsion systems with mode transition	C1 Integrated vehicle health management C2 Adaptive materials and morphing structures C3 Multidisciplinary analysis, design, and optimization C4 Next-generation polymers and composites C5 Noise prediction and suppression C6a Innovative high-temperature metals and environmental coatings C6b Innovative load suppression, and vibration and aeromechanical stability control C8 Structural innovations for high-speed rotorcraft C9 High-temperature ceramics and coatings C10 Multifunctional materials	D1 Advanced guidance systems D2 Distributed decision making, decision making under uncertainty, and flight path planning and prediction D3 Aerodynamics and vehicle dynamics via closed-loop flow control D4 Intelligent and adaptive flight control techniques D5 Fault tolerant and integrated vehicle health management systems D6 Improved onboard weather systems and tools D7 Advanced communication, navigation, and surveillance technology D8 Human-machine integration D9 Synthetic and enhanced vision systems D10 Safe operation of unmanned air vehicles in the national airspace	E1 Methodologies, tools, and simulation and modeling capabilities to design and evaluate complex interactive systems E2 New concepts and methods of separating, spacing, and sequencing aircraft E3 Appropriate roles of humans and automated systems for separation assurance, including the feasibility and merits of highly automated separation assurance systems E4 Affordable new sensors, system technologies, and procedures to improve the prediction and measurement of wake turbulence E5 Interfaces that ensure effective information sharing and coordination among ground-based and airborne human and machine agents E6 Vulnerability analysis as an integral element in the architecture design and simulations of the air transportation system E7 Adaptive ATM techniques to minimize the impact of weather by taking better advantage of improved probabilistic forecasts E8a Transparent and collaborative decision support systems E8b Using operational and maintenance data to assess leading indicators of safety E8c Interfaces and procedures that support human operators in effective task and attention management

BOX ES-1 Recommendations to Achieve Strategic Objectives for Civil Aeronautics Research and Technology

1. NASA should use the 51 Challenges listed in Table ES-1 as the foundation for the future of NASA's civil aeronautics research program during the next decade.
2. The U.S. government should place a high priority on establishing a *stable* aeronautics R&T plan, with the expectation that the plan will receive sustained funding for a decade or more, as necessary, for activities that are demonstrating satisfactory progress.
3. NASA should use five Common Themes to make the most efficient use of civil aeronautics R&T resources:

    - Physics-based analysis tools
    - Multidisciplinary design tools
    - Advanced configurations
    - Intelligent and adaptive systems
    - Complex interactive systems

4. NASA should support fundamental research to create the foundations for practical certification standards for new technologies.
5. The U.S. government should align organizational responsibilities as well as develop and implement techniques to improve change management for federal agencies and to assure a safe and cost-effective transition to the air transportation system of the future.
6. NASA should ensure that its civil aeronautics R&T plan features the substantive involvement of universities and industry, including a more balanced allocation of funding between in-house and external organizations than currently exists.
7. NASA should consult with non-NASA researchers to identify the most effective facilities and tools applicable to key aeronautics R&T projects and should facilitate collaborative research to ensure that each project has access to the most appropriate research capabilities, including test facilities; computational models and facilities; and intellectual capital, available from NASA, the Federal Aviation Administration, the Department of Defense, and other interested research organizations in government, industry, and academia.
8. The U.S. government should conduct a high-level review of organizational options for ensuring U.S. leadership in civil aeronautics.

Chairman CALVERT. The hearing will please come to order.

This afternoon, I want to thank our distinguished panel for appearing before our subcommittee to share their insights and recommendations on NASA's research program. Before getting into the substance of my statement, I want to thank our witnesses for their patience, as we wrestle with today's conflicting schedules, and lead today's hearing. I apologize for the last minute postponement in June. I thank all of you for your willingness to appear today. One schedule conflict we are unable to resolve was getting a NASA witness. Consequently, to ensure all sides are heard, we plan to hold a second hearing in September, featuring that witness.

According to reports by the Aerospace Industries Association, the United States exported more than $67 billion in military and civil aerospace products in 2005. The Aerospace industry is a vital force behind our nation's economic engine, and contributes significantly to our balance of trade. Because our negative balance of trade was at an all time high at the end of 2005, this figure takes on even more importance. Boeing alone is the country's largest exporter of manufactured products, and draws on thousands of suppliers whose products are found on each jet.

The European Union has identified the importance of Aeronautics in its Aeronautics 2020 plan to become the world's leading supplier of aviation products. We in the United States must focus our economic strengths, and invest in high technology sectors to maintain our global leadership. It is important to realize that NASA developed technology can be found in virtually every airplane flying today. The return on the original investment has been tremendous.

With that as a background, NASA's aeronautics program has, in recent years, been prone to changes in leadership and program goals and strategies. There have been four Associate Administrators for Aeronautics Research during the last six years, and each has sought to reshape the program. An inadvertent but undeniable consequence of these changes has been the appearance that the agency has no clear strategic vision, and in the budget constrained environment that all of us must wrestle with, White House and Congressional support for aeronautics R&D has been waning.

Earlier this spring, two reports were issued by the National Research Council that focused on NASA's aeronautics program. One recommended management changes that the agency should consider adopting to ensure maximum science return, especially when dealing with smaller budgets. The second report was the NRC's first ten year plan recommending, in a priority fashion, the kinds of research NASA ought to pursue. Eighty-five aeronautics experts from academia, industry, and federal labs met and worked over a one year period to develop this consensus document. It is my hope that NASA will take it to heart. Other parts of NASA have used similar ten year planning documents with great success, and I see no reason why aeronautics cannot do the same.

The current Associate Administrator for aeronautics research, Dr. Lisa Porter, who has been serving in her position for about nine months, has done an admirable job of restructuring the program under very difficult circumstances. She has been very clear about her intent to refocus and strengthen the fundamental aeronautics research at the agency, as well as develop a broad, cooperative research program with industry. Dr. Porter has committed NASA to work as a full partner with other federal departments and agencies in committing the necessary resources to the Joint Planning and Development Office as it strives to design and implement the Next Generation Air Traffic Management System, and for this, I commend her.

My thanks again to our witnesses and their appearance today. I would now like to recognize my friend and the gentleman from Colorado, Mr. Udall, for his opening statement.

[The prepared statement of Chairman Calvert follows:]

PREPARED STATEMENT OF CHAIRMAN KEN CALVERT

This afternoon I want to thank our distinguished panel for appearing before our subcommittee to share their insights and recommendations on NASA's aeronautics research program. But before getting into the substance of my statement, I want to thank our witnesses for their patience as we wrestled with conflicting schedules that led to today's hearing. I apologize for the last minute postponement in June, and thank all of you for your willingness to appear today. One schedule conflict we were unable to resolve was getting a NASA witness; consequently, to ensure that all sides are heard, we plan to hold a second hearing in September featuring a NASA witness.

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My thanks again to our witnesses for their appearance today. I now recognize the gentleman from Colorado, Mr. Udall, for his opening statement.

Mr. UDALL. I thank the Chairman for yielding. It is great to see Congressman Kucinich and Congresswoman Davis here. We look forward to your testimony.

I think much of my comments are similar to what the Chairman, his remarks focused on. I think we both care deeply about the future of aeronautics in America. Our capability and our accomplishments have long been the envy of the world, and while there is a legitimate concern in some quarters about the competitive threat posed by the European Union, I think that there is a somewhat different perspective you can bring to this situation.

Without minimizing the importance of ensuring that America's aviation industry remains a world leader, I would submit that we should be investing in aeronautics R&D whether or not there was an imminent challenge from Europe or elsewhere.

It is clear that progress in aeronautics is important for reasons beyond simply helping our international trade balance. R&D in aeronautics can enable advances in the capability of America's air transportation system to handle the enormous increases in air travel projected over the next twenty years.

Mr. Chairman, I was just meeting with the DIA leadership team, Denver International Airport, and they had a goal of 2018, I think, about 50 million passengers, and they are telling me they are going to reach that goal, if it is a goal now, in the next 18 to 24 months, as an example.

The R&D efforts can also enable more environmentally compatible aircraft with significantly lower noise emissions and energy consumption relative to aircraft in service today. And this would not only improve our quality of life, but open new markets.

And finally, Aeronautics R&D can lead to new concepts for protecting our nation. However, all of these possibilities can't be realized unless we are making the investments, and I don't believe we are making enough of an investment in R&D.

There was a funding decline of 32 percent between fiscal year 2004 and fiscal year 2007, and there is no improvement in that situation envisioned over the next five years. And similarly, NASA's funding commitment to research on the Next Generation Air Transportation System will be cut in half over the next five years.

One of our witnesses, Dr. Kaminski, warned in the preface to the National Academies' Decadal Survey: "This budgetary trend will make it increasingly difficult for NASA to build a solid foundation for the future." Or to use a word uttered by a previous witness before this committee, it puts NASA's aeronautics program on a path to being irrelevant if not corrected.

And this would be unfortunate, because the Decadal Survey makes it clear that there are research challenges to be overcome if we are to achieve the objectives that I mentioned earlier.

I do want to compliment Dr. Kaminski and the Academies' Aeronautics and Space Engineering Board for producing a thoughtful and comprehensive strategy for federal, and in particular, NASA research in civil aeronautics. And I am particularly impressed with the wide range of experts that were involved.

And I hope that our friends at NASA will give serious consideration to your recommendations, and will continue to seek the Academies' independent advice on these issues, and I also hope that

NASA, and I guess I would say I expect that NASA will move to engage industry and other universities in a meaningful fashion, because we need that kind of collaboration.

But if we don't reverse this budgetary decline that NASA's aeronautics program is undergoing, we are not going to have the robust and vital R&D program that we need and the report envisions.

If the NASA witness were here today, I suspect that the witness would argue that NASA needs to get back to basics and focus on fundamental research in aeronautics. Those days, Mr.——

Chairman CALVERT. Lisa is calling you, too.

Mr. UDALL. I just—I hope she is going to listen.

I would suspect that all of our witnesses would agree with the NASA witness that basic research is essential for underpinning NASA's efforts, and that there has to be a vigorous program of basic aeronautical research.

But the clear message I take away from the two Academy reports, as well as from the testimony of the Aerospace Industries Association, is that while such basic research is necessary, it is clearly not sufficient, if we want to make real progress.

Yet, I see little in NASA's plans that would lead me to believe that NASA is prepared to fund any significant amount of research involving more advanced technological development. Indeed, the opposite appears to be the case. We hear that NASA would like to get rid of its flight research aircraft, and is considering eliminating a number of the aeronautics simulators.

I hope I am wrong, because such direction would run counter to the Aeronautics R&D policy spelled out in the *NASA Authorization Act of 2005.*

I would just like to quote section 411, Mr. Chairman, of that Act. "Congress reaffirms the national commitment to aeronautics research made in the *National Aeronautics and Space Act of 1958.* Aeronautics research and development remains a core mission of NASA. Further, the government of the United States shall promote aeronautics research and development that will expand the capacity, ensure the safety, and increase the efficiency of the Nation's air transportation system, promote the security of the Nation, protect the environment, and retain the leadership of the United States in global aviation."

I hope the individuals in the executive branch tasked with developing a White House aeronautics policy will take those words to heart. We need to ensure that any national policy on aeronautics R&D that emerges properly recognizes the importance of investing in R&D that not only advances our fundamental knowledge, but also is relevant to the needs of our society.

And it should be self-evident that an aeronautics R&D policy statement promulgated by the Administration that is not followed by a commitment of the resources commensurate with the national needs in aeronautics will be a hollow policy indeed.

Mr. Chairman, thank you. I know we have got a lot to discuss today. Again, I welcome my two colleagues. I yield back whatever time I have remaining, which is probably nothing.

Thank you.

[The prepared statement of Mr. Udall follows:]

PREPARED STATEMENT OF REPRESENTATIVE MARK UDALL

Good afternoon. I'd like to join the Chairman in welcoming our witnesses to today's hearing. We have a distinguished group of experts appearing before us, and I look forward to hearing their testimony.

It is no secret that I care deeply about the future of aeronautics in America. Our aeronautics research capability and accomplishments have long been the envy of the world.

While there is legitimate concern in some quarters about the competitive threat posed by the European Union's plans for a significant and sustained thrust in aeronautics research, I have a somewhat different perspective.

Without minimizing the importance of ensuring that America's aviation industry remains a world leader, I would submit that we should be investing in aeronautics R&D *whether or not* there was an imminent competitiveness challenge from Europe or elsewhere.

It's clear that progress in aeronautics is important for reasons beyond simply helping our international trade balance. Aeronautics R&D can enable advances in the capability of America's air transportation system to handle the enormous increases in air travel projected over the next twenty years.

Aeronautics R&D can also enable more environmentally compatible aircraft, with significantly lower noise, emissions, and energy consumption relative to aircraft in commercial service today. Such new aircraft would not only improve our quality of life but would also open new markets. Finally, aeronautics R&D can lead to new concepts for protecting our nation.

However, all of these good things will only be possible if we are committed to making the investments in R&D that are necessary for achieving our research goals. The unfortunate reality is that America is *not* investing enough in such R&D.

Indeed, the Administration's budget plan for NASA's aeronautics program would have aeronautics funding decline by 32 percent between FY 2004 and FY 2007—with no improvement in that situation envisioned over the next five years. Similarly, NASA's funding commitment to research on the next generation air transportation system would be cut in half over the next five years.

As one of our witnesses, Dr. Kaminski, warned in the preface to the National Academies' Decadal Survey of Aeronautics: *"This budgetary trend will make it increasingly difficult for NASA to build a solid foundation for the future."* Or to use a word uttered by a previous witness before this Committee, it puts NASA's aeronautics program on a path to being *"irrelevant"* if not corrected.

That would be unfortunate, because the Decadal Survey makes it clear that there are a host of research challenges to be overcome if we are to achieve the objectives I mentioned earlier.

Indeed, I want to compliment Dr. Kaminski and the Academies' Aeronautics and Space Engineering Board for producing a thoughtful and comprehensive decadal strategy for federal—and in particular NASA—research in civil aeronautics over the next decade. I am particularly impressed with the wide range of experts you involved—an inclusiveness that gives the results of your effort a great deal of credibility in my eyes.

I would hope that our friends at NASA will give serious consideration to your recommendations and will continue to seek the Academies' independent advice on these issues—as we in Congress intend to do.

I also hope and expect that NASA will move to engage industry and our universities in a meaningful and sustained fashion—we need such collaboration if we are going to achieve our goals in aeronautics.

However, unless we also reverse the budgetary decline that NASA's aeronautics program is undergoing, we are not going to have the robust and vital R&D program that we need—and that your report envisions.

Basically, the declining budgets for NASA's aeronautics program mean that there is little money available for a robust R&D program that involves government, industry, and academia in both basic research and more advanced technology development and demonstration.

If a NASA witness were here today, I suspect that that witness would argue that NASA needs to "get back to basics" and focus on fundamental research in aeronautics—that such research has been neglected at NASA.

I suspect that all of our witnesses would *agree* with the NASA witness that basic research is an *essential* underpinning for NASA's efforts in aeronautics—there has to be a vigorous program of basic aeronautical research at NASA.

However, the clear message I take away from the two Academy reports, as well as from the testimony of the Aerospace Industries Association, is that while such basic research is *necessary,* it is clearly not *sufficient* if we want to make real progress in meeting national needs with our aeronautics program.

Yet I see little in NASA's plans that would lead me to believe that NASA is prepared to fund any significant amount of research involving more advanced technological development and demonstration efforts. Indeed, the opposite appears to be case—we hear that NASA would like to get rid of its flight research aircraft and is considering eliminating a number of its aeronautics simulators.

I hope I am wrong, because such a direction would run counter to the aeronautics R&D policy spelled out in the *NASA Authorization Act of 2005.*

To quote Sec. 411 of that Act: *"Congress reaffirms the national commitment to aeronautics research made in the* National Aeronautics and Space Act of 1958. *Aeronautics research and development remains a core mission of NASA. Further, the government of the United States shall promote aeronautics research and development that will expand the capacity, ensure the safety, and increase the efficiency of the Nation's air transportation system, promote the security of the Nation, protect the environment, and retain the leadership of the United States in global aviation."*

I would hope that the individuals in the Executive branch tasked with developing a White House aeronautics policy statement will take those words to heart. We need to ensure that any national policy on aeronautics R&D that emerges properly recognizes the importance of investing in R&D that not only advances our fundamental knowledge, but also is relevant to the needs of our society.

And it should be self-evident that an aeronautics R&D policy statement promulgated by the Administration that is not followed by a commitment of resources commensurate with the national needs in aeronautics will be a hollow policy indeed.

Mr. Chairman, we have a great deal to discuss today. I again want to welcome our witnesses, and I look forward to their testimony.

Chairman CALVERT. That is correct. But we thank the gentleman.

I want to also thank our two witnesses for being here today, and certainly, to express their knowledge and passion for aeronautics. Jo Ann, it is great to have you here and in good health. Fantastic.

If you would let Dennis start off, normally, he has a short statement, and then, he is going to submit the balance of his statement for the record. He has another hearing. So, with that, Mr. Kucinich, you are recognized.

Mr. KUCINICH. I thank my colleague, not only for her indulgence, but for the teamwork that we have been able to do on aeronautics over the last few years, and I certainly want to salute the chair for his leadership, and Congress, in aeronautics. Have been tremendously supportive, as have, has the Ranking Members and all Members of the Committee.

Just a few points, and I am, as you know, I am on my way to another committee meeting, on which I am Ranking Member, and I appreciate this opportunity to make a few points.

First of all, that we all understand and agree that NASA's role in aeronautics is fundamental, that NASA's aeronautics programs contribute substantially to the Nation's economy, that civil aeronautics is also a major contributor to this sector's positive balance of trade, contributing $29 billion in 2005 alone, that our NASA workforce is the reason for our aeronautics dominance, and I know that this committee and this Congress have spoken unequivocally in the past few years by keeping aeronautics strong and the NASA authorization and appropriation bills.

Earlier this year, I attempted to offer a bipartisan amendment to increase funding for aeronautics in the budget resolution by $179 million, which would have left funding flat for fiscal year 2007. It was blocked by the Rules Committee. However, the Senate Appropriations Committee reported a bill last week that adds $1 billion to cover emergency costs associated with the loss of the

Space Shuttle. That would free up money for aeronautics. It also included a ban on involuntary reductions in force, protecting the most valuable part of NASA, its world class workforce. And I am hopeful that the House is going to support these provisions in conference.

I thank the Chair for this opportunity, and I would like to submit the balance of my statement for the record.

[The prepared statement of Mr. Kucinich follows:]

PREPARED STATEMENT OF REPRESENTATIVE DENNIS J. KUCINICH

Thank you Chairman Calvert, Ranking Member Udall, and Members of this subcommittee for the opportunity to speak today about aeronautics. Under your leadership, this Congress has been tremendously supportive of aeronautics and I am grateful for that. I am also grateful to my colleague, Representative Jo Ann Davis who has fought for strong aeronautics programs.

NASA's role in aeronautics is fundamental. Its research is important because NASA is able to develop long term, high-risk enabling technologies that the private sector is unwilling to perform because they are too risky or too expensive. In fact, this has historically been the role of government-sponsored research. This is true not only with aeronautics but also with pharmaceutical research, defense research, energy research, and environmental research.

When the government sponsored basic research yields information that could lead to a service or product with profit potential, the private sector transitions from research to development in order to bring it to market. While it is not always as simple as this, it is clear that where there is no basic research, there can be no development. This research has resulted in monumental innovations that affect our daily lives. Its contributions are especially significant in the areas of national security, environmental protection, and airline safety.

NASA's aeronautics programs also contribute substantially to the Nation's economy. The NASA Glenn Research Center in Brook Park, Ohio, for example, is a cornerstone of the state's fragile economy and a stronghold of aeronautics research. In FY04, the economic output of NASA Glenn alone was $1.2 billion per year. It was responsible for over 10,000 jobs and household earnings amounted to $568 million.

Civil aeronautics is also the major contributor to this sector's positive balance of trade, contributing $29 billion in 2005 alone. Aeronautics contributes to a stronger economy by lowering the cost of transportation, enabling a new generation of service based industries like e-commerce to flourish by performing the research that leads to inexpensive and reliable flights.

These are only a few of the reasons that the proposed cuts to aeronautics are so pernicious. Many of the recommendations by the National Academy of Sciences (NAS) are already headed down the path of irrelevancy because we simply won't be able to pay for them. We will be feeling the effects of the proposed cuts—about 25 percent in FY07 alone—immediately in terms of economic jolts and then in the long-term from the loss of innovation. In addition, the Administration's projected further decline of aeronautics research in the out years erodes our workforce by sending a clear signal that funding in the long term is unstable at best, a concern echoed by the NAS reports. Our NASA workforce is the reason for our aeronautics dominance. It is that simple. But the cuts are already causing us to struggle against rising expertise in countries like China as well as an aging scientific and technical workforce at NASA.

This subcommittee and this Congress have spoken unequivocally in the past few years on this issue by keeping aeronautics strong in NASA authorization and appropriations bills. Yet the NASA budget requests have not changed. We are still underfunding the *Vision for Space Exploration,* forcing the agency to take money from smaller programs like aeronautics, the first A in NASA. In the process, we run the risk of taking away one of NASA's great strengths—diversity. If NASA becomes a one trick pony focused almost exclusively on space exploration, NASA as a whole is vulnerable to political wind shifts.

Our priority should be to correct this. Earlier this year, I attempted to offer a bipartisan amendment to increase funding for aeronautics in the Budget Resolution by $179 million, which would have left funding flat for FY07. But it was blocked by the Rules Committee. However, the Senate Appropriations Committee reported a bill last week that adds one billion dollars to cover the emergency costs associated with the loss of Space Shuttle *Columbia.* That would free up money for Aeronautics. It also included a ban on involuntary reductions in force, protecting the most valuable part of NASA, its world-class workforce. The House should support these provisions in conference.

In the long-term, my hope is that this subcommittee will continue to defend aeronautics at NASA. I will most certainly do what I can to help.

Chairman CALVERT. Without objection, the balance of your statement will be entered into the record. We certainly thank you for presence, Mr. Kucinich, and with that, Ms. Davis, you are recognized.

Ms. DAVIS. Thank you, Mr. Chairman, and I want to thank my colleague, Mr. Kucinich, before he leaves, for his support for aeronautics funding, and I think we have worked well on it together.

I really want to thank Ranking Member Udall and you, Mr. Chairman, for all the work that you have done on trying to push the aeronautics funding.

I just want to say that aeronautics funding is important more than just for the trade balance, and I am going to go into that a little bit. The Langley Memorial Aeronautical Laboratory was established in 1917, and as the Nation's first civil aeronautics research laboratory, under the charter of the National Advisory Committee for Aeronautics. That was the precursor to the modern day NASA. And I am proud to represent the engineers and the researchers who have made the United States' aeronautics research and testing the envy of the world for over 88 years. As you know, NASA Langley Research Center is located in my district.

My concern is that we may have been the envy of the world for over 88 years, but I don't think we are going to continue to be the envy of the world. 1994, just 12 years ago, the aeronautics budget was $1.54 billion, with a B, dollars. This year, the President's request was $724 million for aeronautics programs. That is half. There is no reason in my mind that 12 years later, we should be putting half of what the aeronautics research was twelve years ago.

The Europeans, and I understand what Congressman Udall said, the Europeans are moving forward with a robust investment in research and development, and they appear to be implementing their strategy that they put in, to have their Aeronautics Vision for 2020. I don't think we have an Aeronautics Vision.

I know that in Chairman Wolf's appropriations bill last year, he required that we have an aeronautics policy. I have yet to see it. And I have got serious concerns that the United States is losing their critical expertise in aeronautics research and development. And I think it is going to have a tragic impact on our military, not just our trade balance, but on our military and our civilian aviation.

The U.S. military has benefited significantly from NASA aeronautics research. The single most important benefit of the Department of Defense and NASA Langley's partnership is in the application of new technologies to this nation's military aircraft. Every aviation asset in our military inventory was designed with the help of NASA experts, and NASA conducted wind tunnel tests for the Department of Defense or their contractors on just about every military aircraft that our nation has built.

Not only has, and let me just say that I hope and pray that we don't see the day that our military aircraft is tested and built from research done in Europe. Not only have NASA researchers made

U.S. military vehicles technologically superior, but they have helped determine the capabilities of our enemies, by testing and analyzing foreign warplanes for the defense and intelligence communities. Without proper funding, this capability will perish, and it will be exceedingly difficult to restore.

In addition, the U.S. aviation industry, which plays an important role in the U.S. economy, has benefited from NASA research. I know that aeronautics research is roughly, right now, nine percent of our country's GDP. I don't think it is going to stay that way with the way we are funding aeronautics. While U.S. aeronautics research and testing programs are declining, countries in Europe and elsewhere are investing heavily in aeronautics research. The health of the U.S. aviation industry depends on aeronautics research and development, especially long-term research that they cannot and probably will not perform themselves, in order to compete in the world market, and we are rapidly losing that capability.

And I know everyone thinks that I am out here asking for aeronautics research dollars because of NASA Langley. I have got to tell you, if NASA Langley were located in California, I would still be arguing for the same thing, because I think it is vital to our national security. I serve on the Armed Service Committee with you, Mr. Chairman. I serve on the House Select Intelligence Committee, and I can tell you aeronautics research is critical to our nation's security.

Given the importance of NASA aeronautics research and testing, I am very concerned that NASA, like I said, does not have a vision for aeronautics programs. I look forward to receiving or seeing their vision before the year is out. I hope it is not too late when we receive it.

From NASA's recent aeronautics budget proposals, and other decisions made by senior leadership, it is becoming evident that NASA does not want to participate in any civil aeronautics programs which do not support the *Vision for Space Exploration.* And let me just say I am not against space exploration, but I am against space exploration at the expense of aeronautics research.

This seems to be in direct conflict with Congress' intent, as expressed in the NASA Authorization Bill passed by the House last year. We have received several reports from the National Institute of Aerospace, the National Academies, and others who also conclude that there are major challenges for civil aeronautics in the future that will require continued investment to overcome.

I can't stress enough the importance of aeronautics research. I think it is obvious. And I am going to leave it at that, Mr. Chairman, and ask you, to be able to submit my complete statement for the record.

And I appreciate your concern, and I think you understand the concern, I think those on this committee understand the concern, and I hope that we will not stop letting our voices be heard.

Thank you, Mr. Chairman.

[The prepared statement of Ms. Davis follows:]

PREPARED STATEMENT OF REPRESENTATIVE JO ANN DAVIS

Mr. Chairman: Thank you for the opportunity to speak before your subcommittee this morning on the National Academy's Decadal Survey on Civil Aeronautics and the general subject of our nation's investment in aeronautics research. I appreciate you holding a hearing on this subject, which is important not only to NASA Langley in my district, but also to our nation. Also, I appreciate Congressman Kucinich's appearance here this morning on behalf of NASA Glenn Research Center in Ohio.

The Langley Memorial Aeronautical Laboratory was established in 1917 as the Nation's first civil aeronautics research laboratory under the charter of the National Advisory Committee for Aeronautics, the precursor to the modern-day NASA. I am proud to represent the engineers and researchers who have made United States aeronautics research and testing the envy of the world for over eighty-eight years.

Mr. Chairman, there is no doubt that we have been pioneers in this highly specialized field for most of the last century. My concern is that recent and future cuts will simply make us unable to retain this advantage in the future. For example, the total spending on Aeronautics Research for Fiscal Year 1994 was $1.54 BILLION.

This year, the President's budget requested ONLY $724 million for Aeronautics programs. The Europeans are moving forward with a robust investment in research and development and appear to be implementing the strategy of the European Aeronautics Vision for 2020 that was announced in 2001.

I have serious concerns that the United States is losing critical expertise in aeronautics research and development. This degradation will have a tragic impact on military and civilian aviation, which contributes significantly to our country's national defense and economy.

The U.S. military has benefited tremendously from NASA aeronautics research. The single most important benefit of the Department of Defense and NASA Langley's partnership is in the application of new technologies to this nation's military aircraft. Every aviation asset in the military's inventory was designed with the help of NASA's experts, and NASA conducted wind tunnel tests for the Department of Defense or their contractors on just about every military aircraft that our nation has built.

Not only have NASA researchers made U.S. military vehicles technologically superior, they have helped determine the capabilities of our enemies by testing and analyzing foreign warplanes for the defense and intelligence communities. Without proper funding, this capability will perish and will be exceedingly difficult to restore.

In addition, the U.S. aviation industry, which plays an important role in the U.S. economy, has benefited from NASA research. This vital sector of our economy employs over two million Americans and comprises roughly nine percent of our country's Gross National Product (GNP). This strength is a direct result of the investment in aeronautics research over the past several decades. Nonetheless, the industry has been declining over the past several years and now only holds fifty percent of the world market.

While U.S. aeronautics research and testing programs are declining, countries in Europe and elsewhere are investing heavily in aeronautics research. The health of the U.S. aviation industry depends on aeronautics research and development—especially long-term research that they cannot and will not perform themselves—in order to compete in the world market. We are rapidly losing this capability.

Given the importance of NASA aeronautics research and testing, I am very concerned that NASA does not have a vision for aeronautics programs. While I look forward to receiving NASA's Vision for Aeronautics in the near future, there seems to be a detrimental lack of strategic planning for the future of America's civil aeronautics and testing capabilities.

From NASA's recent aeronautics budget proposals and other decisions made by its senior leadership, it is becoming evident that NASA does not want to participate in any civil aeronautics programs which do not support the *Vision for Space Exploration.* This seems to be in direct conflict with Congress' intent as expressed in the NASA Authorization bill passed by the House last year. We have received several reports from the National Institute of Aerospace, the National Academies, and others who all conclude that there are major challenges for civil aeronautics in the future that will require continued investment to overcome.

The importance of aeronautics research is obvious. This is one of the few areas where we actually enjoy a trade surplus with the rest of the world and the government and industry partnership is still has potential for the future. There are still many challenges in the capacity, efficiency and safety of air transportation, and I firmly believe that NASA's developed expertise in these areas must continue with a strong investment by the American taxpayer. We simply cannot afford to lose aeronautics programs that are vital to our country's national defense and economy.

Again, thank you Chairman Calvert for holding a hearing on this important issue. I appreciate all of your work and your staff's work, and thanks also to the witnesses for being here this morning.

Chairman CALVERT. Thank you, and we certainly appreciate your testimony, and without objection, your full statement will be entered into the record.

I just want to add that we wouldn't dream of taking such a fine facility from your state, and relocating it in California.

Ms. DAVIS. I am glad to hear it.

Mr. HONDA. Mr. Chairman.

Mr. ROHRABACHER. The Chairman wouldn't think of that.

Ms. DAVIS. No, it is fantastic.

Mr. HONDA. Mr. Chairman.

Chairman CALVERT. But we do have a lot of excellent research in California also, so we are all in this together. Yes, oh, yes. The gentleman from California, Mr. Honda.

Mr. HONDA. Yes, if I may enter my statement for the record.

Chairman CALVERT. Without objection, all Members may enter their full statements in the record, and without objection, so ordered.

[The prepared statement of Mr. Honda follows:]

PREPARED STATEMENT OF REPRESENTATIVE MICHAEL M. HONDA

Chairman Calvert and Ranking Member Udall, thank you for holding this important hearing today. I believe it is essential that, as NASA considers restructuring its aeronautics program, the important advice being provided by the National Research Council in its two reports that we will hear testimony about today be taken into consideration.

Over the past several years, NASA has undertaken a series of significant overhauls of its aeronautics program, many of them without sufficient Congressional Oversight. Full Cost Accounting has been combined with broad discretionary authority granted to the agency in the FY 2005 Omnibus Appropriations bill to create a situation in which the salaries of vast numbers of Civil Service R&D employees were moved out of project accounts and into general operations, which has created an artificial crisis at the centers that is being used to justify large scale workforce reductions. In his FY 2006 Budget Request, President Bush tried to cut aeronautics programs over 21 percent by FY10, not counting the loss in purchase power due to inflation. Only the actions of the Congress prevented these drastic cuts from taking place.

The decisions NASA and the Administration are making seem to fly in the face of a number of recommendations made by expert panels. A RAND Corporation panel recommended that "of the 31 existing major NASA test facilities, 29 constitute the 'minimum set' of facilities important to retain and manage to serve national needs." A National Academies committee concluded that "although a strong national program of aeronautics research and technology [R&T] may not, by itself, ensure the competitiveness of the U.S. aviation industry, the committee agrees with earlier studies that without it, the United States is likely to become less competitive in aeronautics relative to countries with stronger programs. Aviation is an R&T-intensive industry.. . .Some aeronautics R&T programs have produced 'breakthroughs' that are immediately usable.. . .More often, aeronautics R&T advances are evolutionary, and a substantial number of years can pass before the aviation systems making use of these advances enter service." This last statement is particularly interesting in light of the fact that NASA is currently saying that it is going to focus only on "breakthrough" technologies.

In the *NASA Authorization Act of 2005,* this committee recognized the shortsightedness of the Administration's plans to shut down key aeronautics test facilities and included language to keep these facilities open. Unfortunately, there are reports that as part of her restructuring of NASA's aeronautics program, the Associate Administrator is considering withdrawing support for facilities such as the "Future Flight Central" simulator, the Vertical Motion Simulator, and the Crew Vehicle Systems Research Facility at the NASA Ames Research Center. I question the wisdom of such actions and hope to hear the witnesses' thoughts on them.

NASA seems to be following a course on aeronautics that has potentially grave consequences not only for its Research Centers and those who work there, in particular the Ames Research Center near my district, but also for our nation. I have many questions that I hope the witnesses can answer, and I look forward to their testimony.

[The prepared statement of Ms. Jackson Lee follows:]

PREPARED STATEMENT OF REPRESENTATIVE SHEILA JACKSON LEE

Mr. Chairman, let me first welcome our witnesses, the Honorable Dennis Kucinich and the Honorable Jo Ann Davis, for testifying today on behalf of their commitment to aeronautics research. I would also like to welcome Mr. Kaminski, Mr. Merrill, Mr. Romanowski, and Mr. Moin. I appreciate the opportunity today to speak with the research community about the purpose, direction, and effectiveness of NASA's aeronautics research program.

Every ten years, the National Academy of Sciences releases a decadal survey of civil aeronautics analyzing the value of current research initiatives, as well as a broad discussion of the benefits future research should pursue.

I understand that this year's report by highlights four primary targets to maximize strategic benefit: 1) Increase capacity, 2) improve safety and reliability, 3) increase efficiency and performance, and 4) reduce energy consumption and environmental impact.

The National Academy of Sciences committee also published 51 research and development challenges that must be overcome in order to achieve the objectives I just mentioned.

I urge NASA to take these recommendations seriously. Previously, this decadal survey has been wise and accurate in predicting the benefit of cooperative government and industry research, as well as the importance of maintaining flexibility and adaptability of new technology.

As we consider the testimony today, I hope that the witnesses will be able to shed some light on how NASA can best cope with increasingly constrained budget allowances, as well as the ability of NASA to transfer the knowledge we gain from basic research initiatives into more sophisticated and applicable technologies.

I thank the Chairman for continuing the bipartisan collaboration of this committee, and for his friendly and even-handed efforts to engage all of us in the progress made by this committee. Thank you, Mr. Chairman, and I yield the balance of my time.

Chairman CALVERT. Are there any questions for our witness?

The gentleman from Colorado.

Mr. UDALL. Just briefly, Mr. Chairman, I want to associate myself with the remarks of the gentlelady from Virginia.

She and I serve on the Armed Services Committee. I think her remarks, focusing on national security and military aircraft, are right on point, and I would remind everybody listening, and also those who would read the transcript, that I don't have a NASA facility like Langley in my district, but I believe this is very, very crucial, and your remarks resonate, because I do know that were you to represent a district that didn't have NASA Langley, you would still be deeply committed to this aeronautics initiative, because of all the reasons you outlined.

So, thank you for taking time to testify today.

Chairman CALVERT. I thank the gentleman. Questions? I thank the gentlelady. Thank you very much for coming.

Okay, next, we have our witnesses for the next panel. If they would like to please come up: Dr. Paul Kaminski, the Chairman of the Steering Committee of the National Research Council's "Decadal Survey of Civil Aeronautics;" Dr. Steve Merrill, the Study Director of the National Research Council "Aeronautics Innovation: NASA's Challenges and Opportunities;" Dr. Michael Romanowski, Vice President for the Civil Aviation, Aerospace Industries Association; Dr. Parviz Moin, Professor, Mechanical Engineering, Stanford University, Director, Institute for Computational and Mathematical Engineering.

Thank you gentlemen for coming to Washington, and with that, we attempt to keep the testimony to five minutes, where we have plenty of time for questions and answers.

So, with that, Dr. Kaminski, I would say Doctor, but all you would start at the same time, so we will start with Dr. Kaminski. You are recognized for five minutes.

Dr. KAMINSKI. Thank you, Mr. Chairman.

Chairman CALVERT. But turn your mike on there, Doctor, excuse me.

Dr. KAMINSKI. Thank you, Mr. Chairman, and Members of the Committee. I would like to submit my full statement for the record, and just provide short excerpts of the portions——

Chairman CALVERT. Without objection, all the witness' full testimony will be entered into the record.

STATEMENT OF DR. PAUL G. KAMINSKI, CHAIRMAN, STEERING COMMITTEE, NATIONAL RESEARCH COUNCIL'S "DECADAL SURVEY OF CIVIL AERONAUTICS"

Dr. KAMINSKI. My name is Paul Kaminski. I am the Chairman and CEO of Technovation, Incorporated, and a senior partner in Global Technology Partners. I am appearing before you today in my capacity as the chair of the National Research Council's Committee on the Decadal Survey of Civil Aeronautics.

The National Research Council is an arm of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine of the National Academies, and was chartered by the Congress in 1863, to advise the government on matters of science and technology.

In 2005, NASA requested that the National Research Council establish a committee on the Decadal Survey of Civil Aeronautics, under the auspices of the Aeronautics and Space Engineering Board. This committee was charged with developing an overarching roadmap for the investment in aeronautics research and technology at NASA, and assessing how federal agencies can more effectively address key issues and challenges. Our report was released in June of 2006, and it is available for insertion of the record, if it has not already——

[The information follows:]

DECADAL SURVEY OF CIVIL AERONAUTICS

Foundation for the Future

Steering Committee for the Decadal Survey of Civil Aeronautics

Aeronautics and Space Engineering Board

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Executive Summary

The U.S. air transportation system is a key contributor to the economic vitality, public well-being, and national security of the United States. The next decade of U.S. civil aeronautics research and technology (R&T) development should provide a foundation for achieving four high-priority Strategic Objectives:

- Increase capacity.
- Improve safety and reliability.
- Increase efficiency and performance.
- Reduce energy consumption and environmental impact.

Civil aeronautics R&T should also consider two lower-priority Strategic Objectives:

- Take advantage of synergies with national and homeland security.
- Support the space program.

The purpose of the Decadal Survey of Civil Aeronautics is to develop a foundation for the future—a decadal strategy for the federal government's involvement in civil aeronautics, with a particular emphasis on the National Aeronautics and Space Administration's (NASA's) research portfolio. A quality function deployment (QFD) process was used to identify and rank 89 R&T Challenges in relation to their potential to achieve the six Strategic Objectives listed above.[1] That process produced a list of 51 high-priority R&T Challenges that must be overcome to further the state of the art (see Table ES-1). These high-priority Challenges are equally divided among five R&T Areas:

- Area A: Aerodynamics and aeroacoustics.
- Area B: Propulsion and power.
- Area C: Materials and structures.
- Area D: Dynamics, navigation, and control, and avionics.
- Area E: Intelligent and autonomous systems, operations and decision making, human integrated systems, and networking and communications.

Advances in these Areas would have a significant, long-term impact on civil aeronautics. Accordingly, federal funds, facilities, and staff should be made available to advance the high-priority R&T Challenges in each Area.

Five Common Themes summarize threads of commonality among the 51 high-priority R&T Challenges:

- Physics-based analysis tools to enable analytical capabilities that go far beyond existing modeling and simulation capabilities and reduce the use of empirical approaches.
- Multidisciplinary design tools to integrate high-fidelity analyses with efficient design methods and to accommodate uncertainty, multiple objectives, and large-scale systems.
- Advanced configurations to go beyond the ability of conventional technologies and aircraft to achieve the Strategic Objectives.
- Intelligent and adaptive systems to significantly improve the performance and robustness of aircraft and the air transportation system as a whole.
- Complex interactive systems to better understand the nature of and options for improving the performance of the air transportation system, which is itself a complex interactive system.

These Themes are not an end in themselves; they are a means to an end. Each Theme describes enabling approaches that will contribute to overcoming multiple Challenges in the five R&T Areas. Exploiting the synergies identified in each

[1] QFD is a group decision-making methodology often used in product design.

TABLE ES-1 Fifty-one Highest Priority Research and Technology Challenges for NASA Aeronautics, Prioritized by R&T Area

A Aerodynamics and Aeroacoustics	B Propulsion and Power	C Materials and Structures	D Dynamics, Navigation, and Control, and Avionics	E Intelligent and Autonomous Systems, Operations and Decision Making, Human Integrated Systems, Networking and Communications
A1 Integrated system performance through novel propulsion–airframe integration A2 Aerodynamic performance improvement through transition, boundary layer, and separation control A3 Novel aerodynamic configurations that enable high performance and/or flexible multi-mission aircraft A4a Aerodynamic designs and flow control schemes to reduce aircraft and rotor noise A4b Accuracy of prediction of aerodynamic performance of complex 3-D configurations, including improved boundary layer transition and turbulence models and associated design tools A6 Aerodynamics robust to atmospheric disturbances and adverse weather conditions, including icing A7a Aerodynamic configurations to leverage advantages of formation flying A7b Accuracy of wake vortex prediction, and vortex detection and mitigation techniques A9 Aerodynamic performance for V/STOL and ESTOL, including adequate control power A10 Techniques for reducing/mitigating sonic boom through novel aircraft shaping A11 Robust and efficient multidisciplinary design tools	B1a Quiet propulsion systems B1b Ultraclean gas turbine combustors to reduce gaseous and particulate emissions in all flight segments B3 Intelligent engines and mechanical power systems capable of self-diagnosis and reconfiguration between shop visits B4 Improved propulsion system fuel economy B5 Propulsion systems for short takeoff and vertical lift B6a Variable-cycle engines to expand the operating envelope B6b Integrated power and thermal management systems B8 Propulsion systems for supersonic flight B9 High-reliability, high-performance, and high-power-density aircraft electric power systems B10 Combined-cycle hypersonic propulsion systems with mode transition	C1 Integrated vehicle health management C2 Adaptive materials and morphing structures C3 Multidisciplinary analysis, design, and optimization C4 Next-generation polymers and composites C5 Noise prediction and suppression C6a Innovative high-temperature metals and environmental coatings C6b Innovative load suppression, and vibration and aeromechanical stability control C8 Structural innovations for high-speed rotorcraft C9 High-temperature ceramics and coatings C10 Multifunctional materials	D1 Advanced guidance systems D2 Distributed decision making, decision making under uncertainty, and flight-path planning and prediction D3 Aerodynamics and vehicle dynamics via closed-loop flow control D4 Intelligent and adaptive flight control techniques D5 Fault-tolerant and integrated vehicle health management systems D6 Improved onboard weather systems and tools D7 Advanced communication, navigation, and surveillance technology D8 Human–machine integration D9 Synthetic and enhanced vision systems D10 Safe operation of unmanned air vehicles in the national airspace	E1 Methodologies, tools, and simulation and modeling capabilities to design and evaluate complex interactive systems E2 New concepts and methods of separating, spacing, and sequencing aircraft E3 Appropriate roles of humans and automated systems for separation assurance, including the feasibility and merits of highly automated separation assurance systems E4 Affordable new sensors, system technologies, and procedures to improve the prediction and measurement of wake turbulence E5 Interfaces that ensure effective information sharing and coordination among ground-based and airborne human and machine agents E6 Vulnerability analysis as an integral element in the architecture design and simulations of the air transportation system E7 Adaptive ATM[a] techniques to minimize the impact of weather by taking better advantage of improved probabilistic forecasts E8a Transparent and collaborative decision support systems E8b Using operational and maintenance data to assess leading indicators of safety E8c Interfaces and procedures that support human operators in effective task and attention management

[a]ATM, air traffic management; V/STOL, vertical and/or short takeoff and landing; ESTOL, extremely short takeoff and landing.

Common Theme will enable NASA's aeronautics program to make the most efficient use of available resources.

Even if individual R&T Challenges are successfully overcome, two key barriers must also be addressed before the Strategic Objectives can be accomplished:

- *Certification.* As systems become more complex, methods to ensure that new technologies can be readily applied to certified systems become more difficult to validate. NASA, in cooperation with the Federal Aviation Administration (FAA), should anticipate the need to certify new technology before its introduction, and it should conduct research on methods to improve both confidence in and the timeliness of certification.
- *Management of change, internal and external.* Changing a complex interactive system such as the air transportation system is becoming more difficult as interactions among the various elements become more complex and the number of internal and external constraints grows. To effectively exploit R&T to achieve the Strategic Objectives, new tools and techniques are required to anticipate and introduce change.

This report also encourages NASA to do the following:

- Create a more balanced split in the allocation of aeronautics R&T funding between in-house research (performed by NASA engineers and technical specialists) and external research (by industry and/or universities). As of January 2006, NASA seemed intent on allocating 93 percent of NASA's aeronautics research funding for in-house use.
- Closely coordinate and cooperate with other public and private organizations to take advantage of advances in cross-cutting technology funded by federal agencies and private industry.
- Develop each new technology to a level of readiness that is appropriate for that technology, given that industry's interest in continuing the development of new technologies varies depending on urgency and expected payoff.
- Invest in research associated with improved ground and flight test facilities and diagnostics, in coordination with the Department of Defense and industry.

The eight recommendations formulated by the steering committee and set forth in Box ES-1 summarize action necessary to properly prioritize civil aeronautics R&T and achieve the relevant Strategic Objectives. This report should provide a useful foundation for the ongoing effort in the executive branch to develop an aeronautics policy. In addition, even though the scope of this study purposely did not include specific budget recommendations, it should support efforts by Congress to authorize and appropriate the NASA aeronautics budget.

BOX ES-1
Recommendations to Achieve Strategic Objectives for Civil Aeronautics Research and Technology

1. NASA should use the 51 Challenges listed in Table ES-1 as the foundation for the future of NASA's civil aeronautics research program during the next decade.
2. The U.S. government should place a high priority on establishing a *stable* aeronautics R&T plan, with the expectation that the plan will receive sustained funding for a decade or more, as necessary, for activities that are demonstrating satisfactory progress.
3. NASA should use five Common Themes to make the most efficient use of civil aeronautics R&T resources:
   - Physics-based analysis tools
   - Multidisciplinary design tools
   - Advanced configurations
   - Intelligent and adaptive systems
   - Complex interactive systems
4. NASA should support fundamental research to create the foundations for practical certification standards for new technologies.
5. The U.S. government should align organizational responsibilities as well as develop and implement techniques to improve change management for federal agencies and to assure a safe and cost-effective transition to the air transportation system of the future.
6. NASA should ensure that its civil aeronautics R&T plan features the substantive involvement of universities and industry, including a more balanced allocation of funding between in-house and external organizations than currently exists.
7. NASA should consult with non-NASA researchers to identify the most effective facilities and tools applicable to key aeronautics R&T projects and should facilitate collaborative research to ensure that each project has access to the most appropriate research capabilities, including test facilities; computational models and facilities; and intellectual capital, available from NASA, the Federal Aviation Administration, the Department of Defense, and other interested research organizations in government, industry, and academia.
8. The U.S. government should conduct a high-level review of organizational options for ensuring U.S. leadership in civil aeronautics.

Chairman CALVERT. We will make sure that the entire report will be entered into the record.

Dr. KAMINSKI. This report, the product of our Decadal Survey, provides a foundation for the future, a 10 year foundation, a decadal strategy for the Federal Government's involvement in civil aeronautics, with a particular emphasis on the NASA research portfolio.

The U.S. air transportation system is indeed a key contributor to the economic vitality, the public well-being, and the national security of the United States. In the absence of an existing national policy for aeronautics, our committee needed to do some work to establish some foundation for how we would set priorities in a research program.

So, we first established four high priority strategic objectives related to our national air transportation system, and those four were to continue to increase the capacity of the system, to continue to improve the safety and reliability of the system, to increase efficiency and performance, and to reduce energy consumption and environmental impact. Those were the four primary.

We also felt that there are two other lower priority objectives that we should consider. Those were to give credit for and take advantage of synergies with national and homeland security in this technology base, and finally, to support the space program. The way we went about our prioritization was to apply something called a quality function deployment process, which is often used to rank competing objectives. And we used this to rank 89 different research and technology challenges that our panel has considered.

And what I would like to do is illustrate by using the chart, how we went about doing this, if I could have the first chart, please. If you look across the columns of this chart, Mr. Chairman, you see the strategic objectives that I spoke about earlier, and each one of those objectives has a weighting factor that we use to establish priorities.

So improving the capacity of our air transportation, and improving safety and reliability had a weight of 5. Improving efficiency of performance and also energy and the environment had a weight of 3. And then, the two lower priority items that I stated, the benefit of synergies with national and homeland security, and support to space received a 1.

What we did, then, was took each R&T challenge, as indicated in those rows, for example, R&T Challenge 1, and if we concluded that it was a major contributor to improved capacity, it got a 9. If it was only an intermediate contributor, it would get a score of 3, and if it was a very small or negligible contributor, it would get a 1. So, you see, by example, the first challenge, we gave that a score of 9 for capacity, a score of 9 for safety and reliability, the next two were 3s, and then, 1s and 1s. So, if you multiply the score by the weight above it, and then add all those numbers up, you end up with a total of 110 for national priority for challenge #1.

Now, we did it in this manner, as I said, absent a national priority, so we constructed our own, and we also did it in an explicit way, so someone who had a different set of weights could go back through here with a different set of weights, and reach their own conclusion. But we wanted to do it in an orderly and a systematic way.

Also, since we were directing our attention towards the NASA research budget, we developed four rating factors for why should this be in the NASA budget, because something might be important in the national priority, but it might be covered better elsewhere. And the factors we considered for why should it be in the NASA budget related to one, did NASA have a supporting infrastructure that could be applied? Was the mission aligned with NASA's mission? Were there a lack of alternative sponsors, that is, if NASA didn't do it, it was likely that nobody would. And finally was the level of risk appropriate for NASA?

So, we assigned scores in each one of those categories, with a weighting of a quarter each, and then, come up with a "Why NASA" composite score, and in this case, it was a 6.0. And so, to come up with an overall composite score, we multiplied the "Why NASA" score of 6.0 by the national priority score of 110, to come up with 660.

So, the outcome of our report, then, was a list of technologies listed by area, in terms of their national priority, in terms of what we felt should be their priority in the NASA budget. So, that is the substance of our report.

These technologies were divided into five areas equally, into aerodynamics and aeroacoustics, in propulsion and power technology, materials and structures, dynamics, navigation and control, and then, into intelligent and autonomous systems. We believe that advances in these areas would have a significant long-term impact on our civil aeronautics program.

We also identified five common themes among these research and technology challenges to provide threads of commonality among the 51 high priority challenges that came out at the top of our priorities. An example of one such theme is the development of physics-based analysis tools, to enable analytical capabilities that go far beyond existing modeling and simulation capabilities, and to reduce the use of empirical approaches to be able to do fundamental basic design.

Each of these themes describes enabling approaches that will contribute to overcoming multiple challenges in these five research and technology areas. And we selected these themes so we could exploit the synergies available among the common elements in the theme, to make better use of limited funds in the NASA aeronautics program.

Finally, to complete our work, we noted that even if we were successful in developing this list of 21 research—51 research and technology challenges, there were two barriers that we faced to effectively exploit the technology for the good of the Nation.

The first of those barriers has to do with certification for civil use. As systems become more complex, methods to ensure that the new technologies can be readily applied to certified systems become more difficult to validate. This is becoming more true with complex software systems, for example, Mr. Chairman. So, we believe that NASA, in cooperation with the FAA, should anticipate the need to certify new technology before its introduction, and it should conduct research on methods to improve both the confidence in and the timeliness of the certification.

And then, secondly, another barrier has to do with the management of change, internal and external, for systems, complex, interactive systems such as our air transportation system. This is becoming more difficult when we have to consider the various factors involved. For example, simply increasing the speed of a civil aircraft may not do any good, if it has to fit into a system where it is scheduled, and has to fly into a slot among slower flying aircraft, so you have to think through the big picture of how we are going to manage change to exploit the technology.

The report also encourages NASA to do the following four things. One, create a more balanced split in the allocation of aeronautics research and technology funding, between in-house research, which is performed by NASA engineers and technical specialists in-house, and external research by universities and industry.

We don't have a final figure for this, but as of January 2006, as best we could determine, the allocation was to be 93 percent of the aeronautics research funding in-house, and only 7 percent contracted outside to university and industry. We believe that should be more in balance.

We also recommended closely coordinating and cooperating with other public and private organizations to take advantage of cross-cutting technology, also developing new technology to a level of readiness that is appropriate for that technology, given the industry's interest in continuing the development of new technologies, depending upon urgency and payoff.

And finally, investing in research associated with improved ground and flight test facilities and diagnostics, in coordination with the Department of Defense and the industry.

Mr. Chairman, in summary, we believe this report should provide a useful foundation for the ongoing effort in the executive branch to develop an aeronautics policy. And in addition, even though the scope of this study did, purposefully, not include specific budget recommendations, it should support efforts by the Congress to authorize an appropriate NASA aeronautics budget.

In closing, I would like to summarize with just two charts that summarize what we believe was the value added of this study. First of all, in the absence of an aeronautics policy, we believe the study helps serve as a de facto set of requirements documents for civil aeronautics research and technology.

Secondly, it in fact demonstrates that we have a target-rich environment for aeronautics research and technology, countering the arguments made by some that this is a mature field, which isn't in need of technology investment.

Thirdly, it prioritizes the research and technology using a quantitative basis that I described, with the flexibility to adjust that if you have a different set of weights. It addresses why NASA should undertake specific research and technology, and identifies opportunities for synergistic research and technology, using the research thrusts and common themes. It also shows that one size does not fit all when setting technology readiness level goals for NASA aeronautics research, and specifies an approach to deal with that.

It emphasized the importance of systems analysis and system integration factors in determining research and technology requirements and programs, and it also identifies barriers that hamper transfer of research and technology results to operational systems.

It shows that a heavily skewed budget allocation that minimizes the participation of academia and industry will impede the timely transfer of research and technology to our industry, and will also, very importantly, impede the growth of new talent in academia and in our supporting base.

It identifies multi-agency issues, and calls for a study of organizational options to facilitate U.S. leadership in civil aeronautics, and it does show the importance of establishing a national aeronautics policy, by demonstrating the impact of strategic objective on research and technology goals and requirements.

Thank you, Mr. Chairman.
[The prepared statement of Dr. Kaminski follows:]

PREPARED STATEMENT OF PAUL G. KAMINSKI

Decadal Survey of Civil Aeronautics: Foundation for the Future

Good afternoon, Mr. Chairman, and Members of the Committee. Thank you for the opportunity to testify before you today. My name is Paul Kaminski. I am the Chairman and Chief Executive Officer of Technovation, Inc., and a senior partner in Global Technology Partners. I appear before you today in my capacity as Chair of the National Research Council's Committee on the Decadal Survey of Civil Aeronautics. The National Research Council is the operating arm of the National Academy of Sciences, National Academy of Engineering, and the Institute of Medicine of the National Academies, chartered by Congress in 1863 to advise the government on matters of science and technology.

In 2005, NASA requested that the National Research Council (NRC) establish the Committee on the Decadal Survey of Civil Aeronautics under the auspices of the Aeronautics and Space Engineering Board. The committee was charged with developing an overarching roadmap for investment in aeronautics research and technology at NASA, and assessing how federal agencies can more effectively address key issues and challenges. Our committee's report was released in June of 2006.

The U.S. air transportation system is a key contributor to the economic vitality, public well-being, and national security of the United States. The next decade of U.S. civil aeronautics research and technology (R&T) development should provide a foundation for achieving four high-priority Strategic Objectives:

- Increase capacity.
- Improve safety and reliability.
- Increase efficiency and performance.
- Reduce energy consumption and environmental impact.

Civil aeronautics R&T should also consider two lower-priority Strategic Objectives:

- Take advantage of synergies with national and homeland security.
- Support the space program.

The purpose of the Decadal Survey of Civil Aeronautics was to develop a foundation for the future—a decadal strategy for the Federal Government's involvement in civil aeronautics, with a particular emphasis on the National Aeronautics and Space Administration's (NASA's) research portfolio. A quality function deployment (QFD) process was used to identify and rank 89 R&T Challenges in relation to their potential to achieve the six Strategic Objectives listed above.[1] That process produced a list of 51 high-priority R&T Challenges that must be overcome to further the state of the art (see Table 1). These high-priority Challenges are equally divided among five R&T Areas:

- Area A: Aerodynamics and aeroacoustics.
- Area B: Propulsion and power.
- Area C: Materials and structures.
- Area D: Dynamics, navigation, and control, and avionics.
- Area E: Intelligent and autonomous systems, operations and decision-making, human integrated systems, and networking and communications.

Advances in these Areas would have a significant, long-term impact on civil aeronautics. Accordingly, federal funds, facilities, and staff should be made available to advance the high-priority R&T Challenges in each Area.

Five Common Themes summarize threads of commonality among the 51 high-priority R&T Challenges:

- Physics-based analysis tools to enable analytical capabilities that go far beyond existing modeling and simulation capabilities and reduce the use of empirical approaches.

[1] QFD is a group decision-making methodology often used in product design.

- Multi-disciplinary design tools to integrate high-fidelity analyses with efficient design methods and to accommodate uncertainty, multiple objectives, and large-scale systems.
- Advanced configurations to go beyond the ability of conventional technologies and aircraft to achieve the Strategic Objectives.
- Intelligent and adaptive systems to significantly improve the performance and robustness of aircraft and the air transportation system as a whole.
- Complex interactive systems to better understand the nature of and options for improving the performance of the air transportation system, which is itself a complex interactive system.

These Themes are not an end in themselves; they are a means to an end. Each Theme describes enabling approaches that will contribute to overcoming multiple Challenges in the five R&T Areas. Exploiting the synergies identified in each Common Theme will enable NASA's aeronautics programs to make the most efficient use of available resources.

Even if individual R&T Challenges are successfully overcome, two key barriers must also be addressed before the Strategic Objectives can be accomplished:

- *Certification.* As systems become more complex, methods to ensure that new technologies can be readily applied to certified systems become more difficult to validate. NASA, in cooperation with the FAA, should anticipate the need to certify new technology before its introduction, and it should conduct research on methods to improve both confidence in and the timeliness of certification.
- *Management of change, internal and external.* Changing a complex interactive system such as the air transportation system is becoming more difficult as interactions among the various elements become more complex and the number of internal and external constraints grows. To effectively exploit R&T to achieve the Strategic Objectives, new tools and techniques are required to anticipate and introduce change.

The report also encourages NASA to do the following:

- Create a more balanced split in the allocation of aeronautics R&T funding between in-house research (performed by NASA engineers and technical specialists) and external research (by industry and/or universities). As of January 2006, NASA seemed intent on allocating 93 percent of NASA's aeronautics research funding for in-house use.
- Closely coordinate and cooperate with other public and private organizations to take advantage of advances in cross-cutting technology funded by federal agencies and private industry.
- Develop each new technology to a level of readiness that is appropriate for that technology, given that industry's interest in continuing the development of new technologies varies depending on urgency and expected payoff.
- Invest in research associated with improved ground and flight test facilities and diagnostics, in coordination with the Department of Defense and industry.

The eight recommendations formulated by the steering committee summarize action necessary to properly prioritize civil aeronautics R&T and achieve the relevant Strategic Objectives:

Recommendation 1. NASA should use the 51 Challenges listed in Table 1 as the foundation for the future of NASA's civil aeronautics research program during the next decade.

Recommendation 2. The U.S. Government should place a high-priority on establishing a *stable* aeronautics R&T plan, with the expectation that the plan will receive sustained funding for a decade or more, as necessary, for activities that are demonstrating satisfactory progress.

Recommendation 3. NASA should use five Common Themes to make the most efficient use of civil aeronautics R&T resources:

- Physics-based analysis tools
- Multi-disciplinary design tools
- Advanced configurations
- Intelligent and adaptive systems
- Complex interactive systems

Recommendation 4. NASA should support fundamental research to create the foundations for practical certification standards for new technologies.

Recommendation 5. The U.S. Government should align organizational responsibilities as well as develop and implement techniques to improve change management for federal agencies and to assure a safe and cost-effective transition to the air transportation system of the future.

Recommendation 6. NASA should ensure that its civil aeronautics R&T plan features the substantive involvement of universities and industry, including a more balanced allocation of funding between in-house and external organizations than currently exists.

Recommendation 7. NASA should consult with non-NASA researchers to identify the most effective facilities and tools applicable to key aeronautics R&T projects and should facilitate collaborative research to ensure that each project has access to the most appropriate research capabilities, including test facilities; computational models and facilities; and intellectual capital, available from NASA, the Federal Aviation Administration, the Department of Defense, and other interested research organizations in government, industry, and academia.

Recommendation 8. The U.S. Government should conduct a high-level review of organizational options for ensuring U.S. leadership in civil aeronautics.

This report should provide a useful foundation for the ongoing effort in the executive branch to develop an aeronautics policy. In addition, even though the scope of this study purposely did not include specific budget recommendations, it should support efforts by Congress to authorize and appropriate the NASA aeronautics budget.

Thank you for the opportunity to testify. I would be happy to take any questions the Committee might have.

COMMITTEE ON DECADAL SURVEY OF CIVIL AERONAUTICS

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ROBERT WHITEHEAD, Aerospace Consultant, Henrico, North Carolina

DIANNE S. WILEY, The Boeing Company, Huntington Beach, California

Biography for Paul G. Kaminski

Paul G. Kaminski is Chairman and CEO of Technovation, Inc., a consulting company dedicated to fostering innovation, and to the development and application of advanced technology. He is also a Senior Partner in Global Technology Partners, a consulting firm specializing in business strategy and investments in technology, defense and aerospace-related companies.

Dr. Kaminski served as the Under Secretary of Defense for Acquisition and Technology from October 3, 1994 to May 16, 1997. He was responsible for all Department of Defense (DOD) research, development, and acquisition programs. He also had responsibility for DOD logistics, environmental security, international programs, the defense industrial base, and military construction. The annual budget for these entities exceeded $100 billion.

Dr. Kaminski has had a continuing career involving large program management, and the development and application of advanced technology in both the private and public sectors. He served as Chairman and Chief Executive Officer of Technology Strategies and Alliances, a technology-oriented investment banking and consulting firm. He has served as Chairman of the Defense Science Board and was a member of the Defense Policy Board. In addition, he has served as a consultant and advisor to a wide variety of government agencies and as a director and trustee of several defense and technology oriented companies.

His previous government experience includes a 20-year career as an officer in the Air Force. During 1981–1984, he served as Director for Low Observables Technology, with responsibility for directing the development, production and fielding of the major "stealth" systems (e.g., F–117, B–2). Prior to that, he served as Special Assistant to the Under Secretary of Defense for Research and Engineering. He also led the initial development of a National Reconnaissance Office space system and related sensor technology. Early in his career, he was responsible for test and evaluation of inertial guidance components for the Minuteman missile and terminal guidance systems for our first precision guided munitions.

Dr. Kaminski is a member of the National Academy of Engineering, a Fellow of the Institute for Electrical and Electronics Engineers, a Fellow of the American Institute of Aeronautics & Astronautics, and a Senior Fellow of the Defense Science Board. He is Chairman of the Board of both Exostar and HRL Labs, and a Director of Bay Microsystems, DFI International, General Dynamics, In-Q-Tel, Inc., and RAND. He serves as an advisor to the Johns Hopkins Applied Physics Lab, LynuxWorks, Inc., MILCOM Technologies and MIT Lincoln Laboratory. He is a member of the Senate Select Committee on Intelligence Technical Advisory Board, the National Reconnaissance Office Technology Advisory Group, the FBI Director's Advisory Board, and the Atlantic Council. He has authored publications dealing with inertial and terminal guidance system performance, simulation techniques, Kalman filtering and numerical techniques applied to estimation problems.

Dr. Kaminski has received the following awards: Department of Defense Medal for Distinguished Public Service (three awards), Defense Distinguished Service Medal, Director of Central Intelligence Director's Award, Defense Intelligence Agency Director's Award, Legion of Merit with Oak Leaf Cluster, Air Force Academy 2002 Distinguished Graduate Award, the International Strategic Studies Association Stefan T. Possony Medal for Outstanding Contributions to Strategic Progress through Science and Technology, the AOC Gold Medal, the Netherlands Medal of Merit in Gold, the French Republic Legion d'Honneur, and the Air Force Systems Command Scientific Achievement Award.

Dr. Kaminski was born in Cleveland, Ohio. He received a Bachelor of Science from the Air Force Academy, Master of Science degrees in both Aeronautics and Astronautics and in Electrical Engineering from the Massachusetts Institute of Technology, and a Ph.D. in Aeronautics and Astronautics from Stanford University. He and his wife, Julie, have two children.

THE NATIONAL ACADEMIES
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June 15, 2006

Hon. Ken Calvert, Chairman
Space and Aeronautics Subcommittee
2320 Rayburn House Office Building
Washington, D.C. 20515

Chairman Calvert,

Within the last three fiscal years, I have not received any federal funding relevant to the June 21, 2006 hearing on *Redefining Civil Aeronautics R&D at NASA.*

Sincerely,

Paul Kaminski
Chair
Committee on the Decadal Survey of Civil Aeronautics

Chairman CALVERT. I thank the gentleman.

Dr. Merrill, you are recognized for five minutes.

STATEMENT OF DR. STEPHEN A. MERRILL, STUDY DIRECTOR, NATIONAL RESEARCH COUNCIL'S "AERONAUTICS INNOVATION: NASA'S CHALLENGES AND OPPORTUNITIES"

Dr. MERRILL. Thank you very much, Mr. Chairman. My name is Steve Merrill, and I direct the Science, Technology, and Economic Policy, or STEP program, at the National Academies, and was Study Director for a second Academy report this spring on NASA's aeronautics program, called "Aeronautics Innovation: NASA's Challenges and Opportunities." And I appreciate the opportunity today to present the findings of that study.

Our charge, I must underscore, was very different from that of the Decadal Study. Our committee had quite a different composition, and the two projects proceeded quite independently of each other, but I think there are some common features.

STEP was asked by the previous Associate Administrator for the Aeronautics Mission Directorate to look outward from NASA, and indeed, from the aerospace industry, and to identify some private and public sector management techniques, tools, methods, that could accelerate the implementation of NASA-developed technologies by its very diversified set of customers: airframe and aircraft engine manufacturers, the military services, the regulatory and operational arms of the Federal Aviation Administration, and so on.

To provide a broad perspective, the Academy assembled a committee that did include a few stakeholders, for example, a former NASA center director, and a former head of R&D at General Electric. But it also included some experts in public policy and administration, economics, and people with technical backgrounds in as diverse as IT, optoelectronics, energy, and materials. The panel was chaired by Alan Schriesheim, the former Director of Argonne National Laboratory.

So, this panel was a bit more varied in its experience and range of expertise than many that have addressed aeronautics R&D policy in the recent past. By the same token, it was not nearly as steeped in the history of NASA or in aeronautics R&D as the Decadal Study, or others that have been conducted by the ASEB at the Academy.

My written testimony describes the methodology that we followed in our work. The first thing that struck our committee, and that became the focus of the first part of its report, is what has been alluded to already several times, and that is the growing discrepancy between the needs said to be served by NASA's aeronautics program, and the resources available to it.

These needs and opportunities have been reiterated over the past decade by numerous public and private bodies. The Commission on the Future of the U.S. Aerospace Industry, various Academy panels, the National Aerospace Institute, the AIA, among others. Together, they make the case for an expansive government supported NASA-administered R&D program. But instead, the program is shrinking and foundering, oscillating between sets of priorities every year or two. That is not a comment on the quality of the work, which people and groups with more technical expertise have found to be quite high.

The Administration continues to cut the budget, while the Congress wants to hold the line, and possibly increase it, and in the meantime, it appeared to the committee that NASA's strategy has been to spread resources too thinly to ensure their effectiveness.

Why did this concern a committee that was charged with recommending methods of promoting innovation? Precisely because the first principle of modern innovation management in a resource-constrained environment is to identify and support the highest priority projects, and winnow out the less important. Without a sharper mission focus, and clearer priorities agreed upon between Congress and the Administration, the first A at NASA will continue to exist, but in Dr. Schriesheim's terminology, the program will continue on "a glide path to irrelevance."

Clearly, our committee was not asked, nor well constituted to define the government's role in civil aviation, a task that the Decadal Study has undertaken with great thoroughness, nor to recommend in detail what NASA's aeronautics priorities should be, but our report does offer some general guidance.

First, a strategic focus for the Aeronautics Mission Directorate that is in line with budget realities, personnel, and technical capabilities, is likely to result in a somewhat reduced mission scope and portfolio, and therefore, to entail some hard choices. That is not a prescription on the part of our committee, but was a reasonable presumption. But the point is that the program, even with a reduced scope, could have a greater impact on innovation in air transportation.

Second, the portfolio should reflect stakeholder needs, and derive from ongoing consultation with users. This is an obvious point, perhaps, but it was one that is, from time to time, ignored. For example, in the rushed effort to revise the vehicle systems program in preparing the FY 2006 NASA budget.

Third, the portfolio should be closely aligned with the core competencies of the NASA research centers, and external performers that NASA supports. Fourth, the Aeronautics Mission Directorate should continue to have a diversified portfolio, in terms of the stage of technology being pursued, even if that means fewer projects, because the further along the development track, generally, the more costly the effort.

Some users of NASA-developed technologies have limited technical capacity, and/or they operate in a very risk-averse environment. In either case, such users need NASA to take some technologies fairly well along the path toward development and testing.

For this reason, the committee considered, but decided that it was, that refocusing NASA's program on fundamental research, which otherwise might appear to be the best, most reasonable course, given the funding outlook, risks losing the support necessary for the program to compete for resources and risks its ultimate effectiveness.

Finally, there is a strong case for NASA to continue to pursue public good areas of R&D work related to a safe and efficient air traffic management system, environmentally more benign aviation operations, and certification of standards and equipment where the market is unlikely to produce an optimum level of innovation.

If the aeronautics program is more strategically focused, the committee believes there are project, personnel, and financial management practices that NASA could adopt, replicate, or expand that would facilitate implementation of its R&D results, and the report describes a number of them in response to what we were asked to do. But unless consensus is reached on NASA's aeronautics mission, and an adequately supported portfolio is agreed upon, no amount of management advice of the sort we were asked to provide can accomplish very much.

Thank you, Mr. Chairman, Members of the subcommittee. I would be happy to answer any questions.

[Prepared statement of Dr. Merrill follows:]

PREPARED STATEMENT OF STEPHEN A. MERRILL

Mr. Chairman and Members of the Subcommittee, I am Stephen Merrill, Executive Director of the National Acadmies' Program on Science, Technology, and Economic Policy (STEP) , and I am here representing an Academy panel, chaired by Alan Schriesheim, former Director of Argonne National Laboratory, that recently issued a report, *Aeronautics Innovation: NASA's Challenges and Opportunities,* copies of which have been supplied to the Subcommittee. I was the project director. As you know, the Academy is charged by congressional charter of 1863 with providing independent, objective technical and policy advice to the government.

The Aeronautics Research Mission Directorate (ARMD) of NASA—the first "A" in NASA—seeks to create an environment that fosters the application of the results of its R&D program in advanced airframe, engine, emissions, air safety, and air traffic control technologies. Adoption of the technologies developed by NASA is dependent on a variety of government and private sector clients or customers—the airframe and aircraft engine industries, the military services, and the regulatory and operational arms of the Federal Aviation Administration. To help produce a more robust innovation climate, ARMD under the previous associate administrator asked the National Academies' Science, Technology, and Economic Policy (STEP) Board to identify from the private and public sectors practices, tools, and methodologies that could maximize NASA's ability to influence innovation outcomes positively.

The Academies assembled a committee composed of experts in private sector technology management, public policy and administration, and economics. A distinctive feature of this committee was that although it included people experienced in different areas of aeronautics technology development it was not limited to stakeholders but also included experts in information technology, optoelectronics, energy, and materials and their application in industries quite remote from aviation. As a result, although we lacked expertise in every facet of ARMD's program we have a somewhat broader perspective than some other observers and participants. We organized two public workshops, visited three of the NASA research centers engaged in aeronautics R&D (Ames, Glenn, and Langley), and we interviewed center, program, and project managers and others knowledgeable about NASA and the aerospace industry. Finally, we reviewed the large volume of reports published in the past few years on the aerospace industry and government policies affecting it. Although we did not have the benefit of the results of the Academies' Decadal Survey of Civil Aeronautics, we did consult other recent work of the Aeronautics and Space Engineering Board, the Commission on the Future of the Aerospace Industry, the Aerospace Industries Association, the National Institute of Aerospace, and numerous other public and private bodies.

By most of these accounts, the Nation has pressing economic and security needs in aviation ranging from meeting increasing international competition in aircraft and engines to expanding air travel capacity while maintaining safety and reducing adverse environmental impacts. In addressing these needs, NASA can play an important role that is not served by other parties, and previous Academy reports have found that NASA's R&D portfolio generally exhibits high technical merit. In spite of this broad support for a robust federal—and, in particular, NASA—role in civil aeronautics technology development, the aeronautics research budget has declined steadily over several years. This is shown in the accompanying figure, at least through 2000.

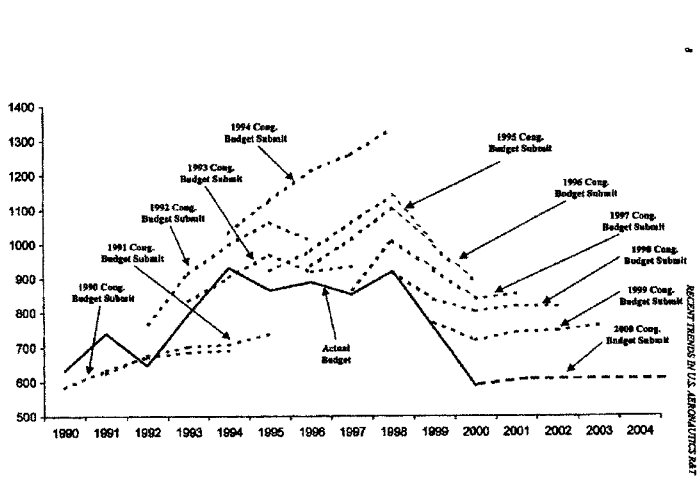

Figure 1-1. NASA Aeronautics R&D Budget Requests and Actual Budgets, 1990-2000

(constant dollars in millions)

Source: NASA.

There is, in fact, a growing discrepancy between the needs said to be served by NASA's program and the resources available to it. Yet there is no agreed upon articulation of what the program should be trying to accomplish in this budget environment. Lacking clear direction from policy-makers, ARMD and its predecessors have been attempting to do as much or more with less, spreading resources too thinly to ensure their effectiveness and the application of the R&D results.

Why did this concern our committee, which was charged with the task of recommending better techniques for transitioning technology? The answer is precisely because modern innovation management in a resource-constrained environment has as a first principle identifying and adequately supporting the highest priority projects and winnowing out the less important ones. Unless ARMD, in consultation with all stakeholders, develops a clear mission focus in better alignment with the resources available to it, any other managerial advice we might offer is of little utility in helping meet the Nation's needs in aeronautics.

This issue, of course, came to a head last year when the President's sharply reduced FY 2006 request for ARMD forced a radical scaling back of plans for the vehicle systems R&D program (VSP), limiting it to the pursuit to the demonstration stage of only four of the technology development activities in its portfolio. In the FY 2006 Appropriations Act, Congress rejected the proposed cut and restored the ARMD budget to its FY 2005 level or slightly above. Now the administration is back with a proposed 20 percent budget reduction in FY 2007 and a new plan to refocus the aeronautics program on fundamental research. Meanwhile, the *NASA Authorization Act of 2005* called on the administration to prepare a policy statement on aeronautics, presumably so that program's future direction can be thoroughly aired and some sort of executive branch-congressional consensus developed. We believe that objective is critical to move the program off what the committee considers "a glide path to irrelevance."

Our committee was not asked nor constituted to redefine the government's role in civil aviation nor to recommend what NASA's aeronautics R&D priorities should be or how the program should be reorganized. We do, however, offer some general guidance in our report.

- A strategic focus for NASA aeronautics that is in line with its budget, personnel, and technical capabilities is likely to result in a reduced mission scope and portfolio, but one with greater potential to achieve innovation in air transportation.

- The portfolio should reflect stakeholder needs. There should be ongoing consultation with customers and users. In our view the behind-closed-doors development of the FY 2006 VSP revision, whatever its technical merits, neglected this lesson.
- The portfolio should also be closely aligned with the core competencies of the NASA research centers and those of the external performers that the agency supports.
- There is a strong case for NASA to continue to pursue "public good" areas of R&D work—those closely related to safe and efficient air traffic management, environmentally more benign aviation operations (i.e., pollution and noise reduction), and the certification of equipment and standards. These are areas where the market is unlikely to produce the optimum level of innovation and where NASA's technical capabilities are in some respects superior to those of regulators and operators.
- If ARMD is to sustain its relevance and support, it should continue to have a portfolio quite diversified in terms of the stage of technology being developed, even if that means significantly fewer projects. Many of the users of NASA-developed technologies have limited technical capability and/or operate in a risk-averse environment. In either case they require outside suppliers to deliver fairly well-proven technologies.
- Refocusing the NASA aeronautics program exclusively on fundamental research may appear to be a reasonable strategy given the current outlook for funding, but it risks losing the support industry stakeholders, without which the program cannot compete effectively for resources.

If the aeronautics R&D program is more strategically focused, the committee believes there are a number of principles derived from innovation management theory and public and private sector practice that would facilitate implementation of NASA-developed aeronautics technologies. We categorize these as transition management tools, flexible personnel practices, and financial management to minimize the disruptive effects of externally imposed demands on resources.

MANAGEMENT FOR TRANSITION

ARMD should implement and regularize for all relevant projects organization-wide a series of management tools aimed at fostering technology transition to users.

- ARMD should cultivate close relationships with external customers and users, engaging them very early in jointly conceptualizing, planning, and prioritization of R&D activities and sustaining regular involvement through the implementation phase.
- ARMD should use decision processes, sometimes referred to as decision gate processes, at predetermined points to establish common expectations among customers, leaders and the technical team throughout the development process, to clarify goals, schedules, deliverables, concrete target performance metrics and review templates, and to set decision criteria and force accountability of all constituents involved. Documented planning for technology transition (i.e., hand-off) to external stakeholders should be a universal managerial practice for all ARMD R&D projects.
- ARMD needs to work aggressively to solidify its reputation as a trustworthy, reliable partner.
- The Joint Planning and Development Office (JPDO), the multi-agency entity charged with developing a plan for a modernized air traffic control system, may be a model for future ARMD technology development projects requiring close external collaboration. The committee could not evaluate the experience with JPDO to date, but it found the concept sufficiently promising to consider employing in other contexts.
- The variety of technologies and the diversity of stakeholder capabilities require increased ARMD flexibility and variability with regard to project time horizons and stage of technology development.

PERSONNEL MANAGEMENT PRACTICES

ARMD should implement more flexible personnel practices, increase incentives for creativity, and actively manage existing constraints on staffing decision-making to minimize their innovation inhibiting effects. Several of these are authorized by the *Space Act of 1958* but are in quite limited use.

- ARMD should increase rotation and seconding of personnel to and from its several research centers and its external partners as a tool for enhancing staffing and access to needed competencies, securing early engagement of partners, and facilitating technology transitioning.
- ARMD should foster external customer contact early in and throughout the careers of technical personnel.
- ARMD should pilot test a dual track, pay-for-performance program similar to that in place at the Air Force Research Laboratory.
- ARMD should allow its R&D personnel some small fraction of their time for “free thinking” and encourage its use by organizing regular events to showcase employee ideas; external stakeholders should be invited to participate in these events.
- NASA should expand its Centennial Challenges program to offer high profile aeronautics prizes of a magnitude sufficient to generate considerable participation and public attention.

FINANCIAL MANAGEMENT

ARMD should structure financial management to minimize the disruptive effects of externally imposed demands on resources and one-size-fits-all accounting rules.

- NASA should modify full-cost pricing for ARMD test facilities use, with charges more closely aligned with marginal costs.
- AMRD should work with the Office of Management and Budget and Congress to establish separate centrally-funded budget lines for national infrastructure and facilities maintenance.
- Because mid-stream changes are in the nature of research and development ARMD should establish greater budget and milestone flexibility through centrally-funded pools and contingency accounts.
- ARMD should explore establishing Working Capital Fund structures for wind tunnels and aeronautics R&D services.
- ARMD should negotiate with congressional sponsors of directed funding and recipients to align mandated activities better with established programs. If this is not possible, directed funding should be separated in budget accounting and in management.

Even if NASA implemented these recommendations regarding transition planning and personnel and financial management, successful innovations would still be impeded by the policy differences and budget realities facing ARMD and its research centers. Until the divide is bridged and a consensus mission supported by adequate resources, this committee’s management advice, although potentially useful, is a secondary priority.

Thank you, Mr. Chairman, for this opportunity to present our findings and recommendations to the Subcommittee. I would be pleased to answer any questions the Members have.

Committee on Innovation Models for Aeronautics Technologies

ALAN SCHRIESHEIM, Argonne National Laboratory (ret.), Chair

MEYER J. BENZAKEIN, Ohio State University

JEROME E. GASPAR, Rockwell Collins

GLENN MAZUR, Japan Business Consultants, Ltd., and University of Michigan (ret.)

HENRY (HARRY) McDONALD, University of Tennessee

DUNCAN T. MOORE, Infotonics Technology Center and University of Rochester

JOSEPH MORONE, Albany International, Inc.

MARK B. MYERS, Wharton School, University of Pennsylvania

NICHOLAS VONORTAS, George Washington University

TODD A. WATKINS, Lehigh University

DEBORAH WINCE-SMITH, Council on Competitiveness

Project Director

STEPHEN A. MERRILL, The National Academies

BIOGRAPHY FOR STEPHEN A. MERRILL

Stephen Merrill has been Executive Director of the National Academies' Board on Science, Technology, and Economic Policy (STEP) since its formation in 1991. With the sponsorship of a growing number of Federal Government agencies, foundations, multi-national corporations in various sectors, and international institutions, the STEP program has become an important discussion forum and authoritative voice on technical standards, trade, taxation, human resources, and statistical as well as research and development policies. At the same time Dr. Merrill has directed several STEP projects and publications, including *Investing for Productivity and Prosperity* (1994); *Improving America's Schools* (1995); *Industrial Research and Innovation Indicators* (1997); *U.S. Industry in 2000: Studies in Competitive Performance and Securing America's Industrial Strength* (1999); *Trends in Federal Support of Research and Graduate Education* (2001); and *A Patent System for the 21st Century* (2004). For his work on the latter project he was named one of the 50 most influential people worldwide in the intellectual property field by *Managing Intellectual Property* magazine and earned the Academies' 2005 Distinguished Service Award.

Dr. Merrill's association with the National Academies began in 1985, when he was principal consultant on the Academy report, *Balancing the National Interest: National Security Export Controls and Global Economic Competition.* As a consultant he also contributed to Academy studies in the areas of science policy, manufacturing, and competitiveness. In 1987 he was appointed to direct the Academies' first government and congressional liaison office. During his tenure as Executive Director of Government and External Affairs the Academies received a steadily increasing number of congressional requests for policy advice.

Previously, Dr. Merrill was a Fellow in International Business at the Center for Strategic and International Studies (CSIS), where he specialized in technology trade issues. For seven years until 1981, he served on various congressional staffs, most recently that of the Senate Commerce, Science, and Transportation Committee, where he organized the first congressional hearings on international competition in biotechnology and microelectronics and was responsible for legislation on technological innovation and the allocation of intellectual property rights arising from government-sponsored research.

Dr. Merrill holds degrees in political science from Columbia (B.A., *summa cum laude*), Oxford (M. Phil.), and Yale (M.A. and Ph.D.) Universities. In 1992 he attended the Senior Managers in Government Program of the John F. Kennedy School of Government at Harvard University. From 1989 to 1996 he was an Adjunct Professor of International Affairs at Georgetown University.

Chairman CALVERT. I thank the gentleman.

Dr. Romanowski, you are recognized.

STATEMENT OF DR. MICHAEL ROMANOWSKI, VICE PRESIDENT FOR CIVIL AVIATION, AEROSPACE INDUSTRIES ASSOCIATION

Dr. ROMANOWSKI. Chairman Calvert, Representative Udall, I would like to thank you and the Space and Aeronautics Subcommittee for the opportunity to testify at today's hearing on behalf of the Aerospace Industries Association.

AIA is the Nation's largest trade organization in the aviation, space, and national defense sectors. Our companies employ 627,000 people in high wage, high skill jobs in all fifty states. AIA has strong views on the status and direction of NASA's aeronautics research program that I would like to discuss today.

Mr. Chairman, in your first question in your preparatory letter, you asked how we would assess the direction of NASA's aeronautics program, and in particular, you asked if NASA's emphasis on foundational research was appropriate. If I can rephrase this to ask is U.S. industry satisfied with the direction of NASA aeronautics, I can respectfully say the short answer is no.

Mr. Chairman, our nation's federal investment in aeronautics research is at a crossroads, and the consequences to our nation are potentially serious. If NASA is to remain at the forefront of aeronautics research, it is critical that significant changes are made to the proposed funding levels and research plans. As Representative Davis highlighted a little earlier, looking at the proposed 2007 funding level of only $724 million, NASA's aeronautics budget is facing a 50 percent reduction over the last 15 years.

Mr. Chairman, AIA applauds the leadership and concern for the state of aeronautics both the Congress and this committee showed last year, when it mandated two very important things. First, it mandated a real increase in NASA's aeronautics funding. It provided a $60 million funding increase above the fiscal year 2006 request. And as Representative Udall highlighted, it also mandated the Administration develop a national aeronautics policy, to reflect the critical role of aeronautics to the long-term U.S. competitiveness. It also required the development of integrated research roadmaps, to drive long-term funding and programmatic decisions. Now, these are long-term, not dependent on just the next budget cycle.

Mr. Chairman, we are extremely concerned that significant cuts and redirection are being made to NASA's aeronautics program before the national aeronautics policy is written and its research roadmaps are delivered. Once made, this direction may be difficult to reverse.

We are also very concerned that NASA is eliminating transitional research, like cutting edge demonstrations or validation activities, including its X-Planes, and focusing only on fundamental research. These transitional programs have proven both highly valuable and inspiring in the past, and they are necessary for the future.

We all know that the U.S. air traffic is at a point close to gridlock. Approximately 10 percent of our U.S. economy is directly tied to aviation, and the failure to develop and implement the next generation air transportation system, or NGATS, will hamper our economic growth.

However, while NASA is sustaining cuts, critical research needed for NGATS is unfunded, missing from the work plans of any government agency, including NASA. The failure to do this important research in a timely way could result in significant delays or problems developing and implementing NGATS. It is estimated that an addition $200 to $300 million per year of transitional research is needed in vital areas to make NGATS a reality.

We applaud the House for recently adding $100 million above the 2007 NASA aeronautics request. However, we note that this will still result in an almost $88 million less than last year's enacted funding level. We respectively request that Congress continue to show its leadership on this issue by providing at least level funding for the 2007 NASA aeronautics budget, while fully funding NASA's space exploration and science activities. We believe that NASA must step up and use those restored funds exclusively on transitional R&D programs, like prototypes and demonstrations needed to develop and implement NGATS.

Mr. Chairman, your second question asks what NASA should do to ensure its research is relevant to the long-term needs of industry, is used by industry, and promotes the development of the aeronautics workforce.

The most important thing, Mr. Chairman, is that NASA should fully engage its government, industry, and academic stakeholders as partners, and they should work together with the stakeholder partners to develop a program that is consistent with national objectives like NGATS, and the roadmaps being developed along the lines of the national aeronautics policy. Key elements of those roadmaps should span advanced fixed-wing and rotary-wing vehicle, propulsion technologies, manned and unmanned systems, subsonic, supersonic, and hypersonic fields.

We are encouraged by the development of the national aeronautics policy and roadmaps. However, we believe that additional collaboration and public review is necessary to ensure that these meet our country's long-term needs. AIA stands ready to assist in any way, as NASA moves forward developing its aeronautics research program.

The final question you asked, Mr. Chairman, was AIA's comments on the conclusions and recommendations of the Decadal Study. First off, I would like to commend Dr. Kaminski and the National Academies on a well-written, concise, and thorough report, and AIA generally agrees with the conclusions and recommendations that are made in the report.

There are two areas we would like to amplify that go beyond the Decadal Study, however, and these are discussed in detail in my written statement. First, the report does not provide the recommended funding profiles for its research priorities, as Dr. Kaminski indicated. We would like to see these in the future. We believe that would help make funding, the proper funding decisions.

And also, the report lists some technologies as a low priority because they impacted only one or two strategic areas. However, these will all play an important part in NGATS, and that raises an important question for us. If NASA will not conduct this type of research, transitional research, who will?

And I thank you once again, Mr. Chairman, for the opportunity to share the perspectives of AIA on the NASA's aeronautics program, and I would welcome any questions that the committee has.

[The prepared statement of Dr. Romanowski follows:]

PREPARED STATEMENT OF MICHAEL ROMANOWSKI

Introduction

Chairman Calvert, on behalf of the Aerospace Industries Association of America (AIA), I wish to thank you, Representative Udall, and the Space and Aeronautics Subcommittee for the opportunity to testify on the status of civil aeronautics research and development (R&D) at NASA. I would like to commend NASA for their commitment to the *Vision for Space Exploration* (VSE) and for requesting the National Academies' study on its workforce. I am honored to serve on this panel.

As you may know, AIA represents more than 100 large companies and 170 smaller business suppliers that employ 627,000 highly skilled workers. We operate as the largest trade association in the United States across three sectors: civil aviation, space systems, and national defense. Maintaining U.S. aviation leadership is critical to our national economic health and national security. Aerospace provides our nation's largest trade surplus ($40 billion in 2005), while U.S. companies continue to invest heavily in R&D, spending more than $50 billion over the last 15 years.

The United States' federal investment in aeronautics research is at a cross roads. Around the world, governments are taking aim at our commercial aviation industry—increasing their investment and making commercially relevant aeronautics R&D a top priority. Meanwhile, the United States continues to de-emphasize non-military aeronautics research. For example, while NASA continues to downsize and internalize its aeronautics program, implementation of the European Union's R&D plan Vision 2020 is accelerating. This trend will have a serious impact on the Nation's competitiveness, national security, and position as the world's leader in aeronautics research. As a result, rather than leading the world in the development of next generation aviation products, services and infrastructure, the United States will take a backseat to the products created by other nations: products supported by policies, rules and incentives designed to disadvantage United States' solutions.

The sections of my testimony, Mr. Chairman, correspond with the three questions that you posed in the witness letter of invitation.

How would you assess the Aeronautics Research Mission Directorate's program goals and strategies? Is NASA's emphasis on foundational research appropriate? Given the resources currently allocated to it, is ARMD properly structured, and is it pursuing the right lines of research?

Mr. Chairman, the United States' role as the world leader in aeronautics is at risk due to sustained cuts to the NASA aeronautics budget. NASA's Aeronautics Research Mission Directorate (ARMD) budget has seen consistent cuts over the last 13 years. From a funding level of $1.54 billion in FY 1994, cuts to the ARMD budget have resulted in a more than 50 percent reduction, with a proposed FY 2007 funding of only $724.4 million.

This committee showed its leadership and concern for the state of aeronautics last year when it mandated in the 2006 *NASA Reauthorization Act* that the administration create a National Aeronautics Policy that reflects the critical role of aeronautics to U.S. long-term competitiveness. This document, scheduled to be completed by November 2006, needs to provide a framework and a roadmap that sets the path for answering the questions that this committee determined as key for the long-term future of domestic aeronautics research and not just the next budget cycle. Instead, significant cuts are being made to the ARMD before the policy is written.

Excessive decreases in funding endanger the future of U.S. leadership in the global aviation industry. The risk is compounded by NASA's redirection and internalization of planned research. If NASA is to remain at the forefront of aeronautics research, it is critical that significant changes are made to the proposed aeronautics funding levels and research plans. The recently marked-up appropriations bill cuts almost $88 million in ARMD funding from last year's enacted level. While NASA is sustaining cuts, critical research for the Next Generation Air Transportation System (NGATS) is unfunded and missing from the work plans of any governmental agency. It is estimated that an additional $200–$300 million of transitional research is needed each year in vital areas such as air traffic modernization, environment and safety in order to implement this important multi-agency system.

With the U.S. air traffic system close to the point of gridlock, only the transformational improvements of NGATS can address capacity shortfalls and other long-term growth needs. The U.S. air transportation system and aviation industry are national assets that directly impact the U.S. economy and drive its long-term growth. They are also integral to national security. Approximately 10 percent of the U.S. economy is directly tied to aviation.

The new NASA ARMD research direction largely eliminates cutting-edge demonstration or validation activities (including X planes) that have proven both highly valuable and inspiring. Abandoning transitional R&D demonstrations removes a major tool used to validate fundamental research projects and to conduct research that cannot be performed in laboratories or on computers. Cutting-edge demonstration or validation programs are also vital for establishing the standards and regulations necessary to field many new capabilities.

NASA plays a critical role in the way Americans view our place in the world; as the world leader in space exploration, science programs and aeronautics research. These programs are far too important to be pitted against one another in annual funding battles. Increased funding for aeronautics research at NASA should not come at the expense of other important agency priorities, but from an overall NASA budget increase. In the FY 2006 NASA budget, Congress took the first step in reversing the detrimental decline in ARMD funding by providing an increase of $60 million over the FY 2006 request. We respectfully request that Congress continue to show leadership on this issue by providing at least level funding of $912.3 million in the FY 2007 NASA aeronautics budget. NASA must step up by using restored funds exclusively on transitional R&D programs with an emphasis on the prototypes and demonstrations needed to develop and implement NGATS.

What should NASA be doing to ensure that its research is relevant to the long-term needs of industry and is used by industry? What should NASA be doing to help keep the academic research enterprise healthy and to ensure an adequate supply of aeronautics engineers and researchers?

This year marks the 50th anniversary of the landmark X–1 project. This project exemplifies the inspiration and vision we need to attract America's best and brightest to aerospace careers. In addition to providing valuable applicable technical knowledge, the X–1 project defined and solidified the post-war cooperative merger between U.S. military needs, industrial capabilities, and research facilities. These are all vital elements of what should be in a national aeronautic policy.

Instead, NASA has retreated from its engagement with industry while focusing program development and execution internally—this must be reversed. NASA must fully engage its government and private sector stakeholders. For example, NASA should plan and conduct its research program in conjunction with government and private sector stakeholders to support the NGATS research needs identified by the Joint Planning and Development Office (JPDO).

Although the development of the National Aeronautics Policy is encouraging, additional collaboration is necessary to ensure that the policy meets our long-term needs. This new policy must ensure continued U.S. leadership and set the vision that lays the foundation for a healthy research enterprise and drives stable budgetary and program decisions across all federal aeronautics R&D. Rather than hosting a one-time meeting to listen to stakeholders, the administration needs to partner with academia, users, and manufacturers to create a transparent public development and review process for the policy.

The policy must be supported by robust technology roadmaps that are developed in concert with government, industry, and academia. The individual scientists and engineers in any of these areas are not in the best position to determine how, when and whether the technologies they investigate will be utilized. It takes industry and government technical leaders working together at the strategic level to determine what research should be pursued. To ensure that programs linked to tactical and strategic roadmap goals are appropriate and adequately supported, regular government stakeholder meetings to evaluate progress, goals, and means should be sponsored by each federal agency that funds aeronautics research. Ensuring a relevant role for the university community will also guarantee that new engineers and scientist graduates have skills that are relevant to their future industry and government employers.

What is your reaction to the conclusions and recommendations of the Decadal Survey?

I commend the National Academies on a well written, concise and thorough report on aeronautic research needed in the next ten years. The Aerospace Industries Association agrees with the five common themes the study identified among the 51 high-priority research challenges. We also agree that NASA needs to create a more balanced split in the allocation of aeronautics R&D funding between in house research (performed by NASA) and external research (by industry and/or universities).

Though we commend the use of the qualified function deployment (QFD) process to rank the need and importance of R&D projects, it is essential to also define their funding needs. When using reports like this to stress the importance of federal R&D spending, without specific figures, these priorities lose importance and are harder to quantify. The QFD also ranks many aeronautic R&D challenges as low priority due to their impact on only one or two "Strategic Objectives." Research in smaller, lighter, and less expensive avionics; more efficient certification processes; design, development, and upgrade processes for complex, software-intensive systems; and secure network-centric avionics architecture and systems all will play a part in NGATS. If NASA will not fulfill its mission directive and conduct this type of transitional research, the question becomes who will?

The American public, our national competitive standing, and industry are adversely affected by dramatic redirection of research priorities. A national policy would minimize dramatic redirecting of aeronautics research and provide industry with confidence regarding future federal research priorities for future business investment.

The National Aeronautics Policy must be consistent with the government's historic research role and promote the continued United States leadership of civil and military aeronautics research, and pragmatically address issues of leadership, vision for the future, relevance of research, and transition from research to development. The policy should support the development and stable funding of integrated research roadmaps in advanced fixed and rotary wing aircraft and propulsion as well as the subsonic, supersonic and hypersonic fields. Industry is willing and prepared to assist the administration in the development of the national policy and subsequent research roadmaps.

Thank you once again, Mr. Chairman, for this opportunity to share the perspectives of AIA on the civil aeronautics R&D at NASA.

Chairman CALVERT. Thank the gentleman.

Dr. Moin, you are recognized.

Dr. MOIN. Mr. Chairman.

Chairman CALVERT. You might check to see if your mike is on.

Dr. MOIN. Oh, sorry.

Chairman CALVERT. There you go.

Dr. MOIN. Mr. Chairman and the honorable Committee Members.

Chairman CALVERT. Your mike still isn't on.

Dr. MOIN. Not working.

Chairman CALVERT. There you go.

STATEMENT OF DR. PARVIZ MOIN, PROFESSOR, MECHANICAL ENGINEERING, STANFORD UNIVERSITY, DIRECTOR, INSTITUTE FOR COMPUTATIONAL AND MATHEMATICAL ENGINEERING

Dr. MOIN. My name is Parviz Moin, and I am a Professor of Mechanical Engineering and Computational Mathematical Engineering at Stanford University.

My field of research is turbine and flow physics and computational aerodynamics and propulsion. I am the editor and on the editorial boards of five international journals on computational methods and flow physics, which keeps me reasonably abreast of global research activity in these areas. Before joining Stanford as a faculty member, I did postdoctoral study at NASA Ames Research Center, and subsequently, was hired as a civil servant research scientist there.

Mr. Chairman, in my testimony, I will address the four questions that you asked me in your invitation letter of June 13, 2006.

In reference to Aeronautics Research Mission Directorate goals and strategies, I do believe that NASA's emphasis on foundational research is very appropriate. Foundational research is precisely what NASA should be doing. In fact, given the limited resources that the Aeronautics Directorate has been allocated, only foundational research is what it can do successfully.

In my opinion, NASA's role in aeronautics research should be as a bridge between academia, which conducts fundamental research, and industry, which ultimately ensures the preeminence of the United States in aerospace technology. As such, NASA should inspire and support the best minds in this country, to carry out fundamental research relevant to aerospace industry. To be an effective bridge, however, NASA engineers and leadership should be of the highest technical caliber, in order to be respected and listened to by both academia and industry. In this regard, Administrator Griffin should be commended for appointing an outstanding technical team at the highest leadership levels of the agency.

The Aeronautics Directorate should strive to preserve the technical expertise that remains at NASA, and more importantly, to make a valiant effort to replenish its technical workforce. In achieving this goal, NASA needs this body's help in alleviating some of the administrative constraints it is facing.

Your second question had to do with the major technological and competitive challenges facing the aeronautics industry. I think the main competitive technical challenge facing the civil aeronautics industry is the projected increase in air traffic capacity in the next ten to fifteen years, and the related performance and environmental issues, such as noise and harmful emissions. Progress in these areas is very much dependent on a better understanding of the underlying physical phenomena, and the subsequent development of high fidelity predictive models.

What is needed here is increased coordinated foundational research in these areas. Considerable emphasis for research along these lines in the recent NASA Research Announcement, NRA, which solicited basic and applied research proposals, demonstrates that the Aeronautics Directorate leadership is clearly aware of these foundational technical challenges, and is taking action to deal with them.

The European Union has already taken the lead in devoting substantial research resources to multinational coordinated research programs for development of high fidelity predictive tools. In recent times, they have been more open in trying new ideas and leading edge technologies.

Japan has been sustaining a strong long-term research program in their aeronautics, and especially in high speed flight, and China has recently expanded its research activity in aerospace science and technology. It is noteworthy that both countries have received major contracts from Boeing. In particular, Japan is manufacturing the main wing-box of the Boeing 787, its latest commercial aircraft.

Although it is not directly related to the near-term competitive challenges facing the civil aeronautics industry, I believe the Aeronautics Directorate has a critical role to play in the area of hypersonics, with application to both manned and robot space exploration missions.

Foundational research in physics-based modeling is required for high speed, large payload planetary entry, descent, and landing. The Aeronautics Directorate has the technical means to take the lead in this area, but the necessary resources, in my opinion, should be provided from the space exploration mission.

Your third question had to do with the emphasis, the renewed emphasis of the Aeronautics Directorate on computational and physics-based modeling. Computational science has been recognized as the third leg of the stool representing 21st Century science, together with theory and experimentation. Computations enable us to investigate phenomena where economics or physical and environmental constraints preclude experimentation. I invite you to see the recent report of President's Information Technology Advisory Committee in this regard.

The last 20 years have seen the rise of computer-aided engineering in almost every technical sector. Today, many aspects of product development, design, optimization, performance analysis, and certification rely heavily on the use of computations. Computers are also the latest resource available for scientific discovery.

Over 30 years ago, the visionary leaders of NASA and its highly acclaimed research staff pioneered the development of the discipline of computational aerodynamics and its transition to industry. Today, computational modeling is an integral part of aircraft and engine design, and is responsible for dramatic reductions in the required expensive wind tunnel and engine tests, as you can see in—I wanted to see the first chart, perhaps—which shows, in this chart, you see the number of tests required, wind tunnel tests, and then, for aircraft, is done for wing design, and shows the number goes down significantly with the introduction of computations. New high fidelity—but I would like to say that the computational modeling is an integral part of aircraft and engine design, and is responsible for dramatic reductions in the required expensive wind tunnel and engine tests.

However, in spite of its successes, computational engineering is far from being predictive for complex engineering systems. New high fidelity methods, physics-based modeling research, computer science, and validation and verification tools, including tighter coupling to laboratory experimentations, are required before achieving predictive status.

Over the past five years alone, the supercomputer power has increased by two orders of magnitude. Because of this, there now exists new opportunities to conduct high fidelity integrated computer simulations of complex engineering systems. Therefore, NASA is clearly correct to increase its emphasis on computational and physics-based modeling. NASA has invested in supercomputer hardware, and should continue to do so. There is also a clear emphasis in computational and physics-based modeling in NASA's recently released NRA. However, to reestablish its technical preeminence in this area, NASA needs to retain its existing knowledgebase, and build on it by carefully complementing and replenishing its workforce with young, talented Ph.D. engineers.

Question number four, and the final question, had to do with the status of recruiting graduate students to the aeronautics programs. There does not appear to be any pronounced decline in the enrollment of graduate students in the top rank aeronautical engineering departments, and in related engineering fields in the United States.

However, a disturbing new phenomenon for NASA is that the agency appears to be a less attractive choice for most of these highly skilled engineering Ph.D. graduates. Back in the late '70s, when I joined NASA, the agency was considered a top competitive career choice for many of the most talented engineers in the country. They were attracted to the agency for its unique research facilities, and for working with and being mentored by some of the most illustrious technical leaders in aeronautics in this country.

According to the 2005 membership directory of the National Academy of Engineering, only two active employees of NASA's aeronautics field centers have the distinction of membership in the Academy. This is disproportionately low for the country's leading aeronautical research enterprise.

Finally, as you are undoubtedly aware, about one half of engineering Ph.D. graduates in the United States are foreign born. Due to various cumbersome and, in my opinion, often unnecessary restrictions, given the global current economy, it is extremely difficult for this technical workforce to be employed by the civil aerospace industry or NASA. I believe it is in our country's best national interest to embrace this enormous technical resource, and provide opportunities for these U.S. graduates for postdoctoral fellowships in NASA, and employment in civil aeronautics industry, and for eventual full citizenship.

[The prepared statement of Dr. Moin follows:]

PREPARED STATEMENT OF PARVIZ MOIN

Mr. Chairman and the honorable Committee Members,

My name is Parviz Moin and I am a Professor of Mechanical Engineering and Computational and Mathematical Engineering at Stanford University. My field of research is turbulent flow physics and computational aerodynamics and propulsion. I am the editor and on editorial boards of five international journals on computational methods and flow physics, which keeps me reasonably abreast of global research activity in these areas. Before joining Stanford as a faculty member, I did a Postdoctoral study at NASA-Ames and subsequently was hired as a civil servant research scientist there.

Mr. Chairman, in my testimony I will address the four questions that you asked me in your invitation letter of June 13, 2006.

1. How would you assess the Aeronautics Research Mission Directorate's (ARMD) program goals and strategies? Is NASA's emphasis on foundational research appropriate? Given the resources currently allocated to it, is ARMD properly structured, and is it pursuing the right lines of research?

In reference to Aeronautics Research Mission Directorate (ARMD) goals and strategies, I do believe that NASA's emphasis on foundational research is very appropriate. Foundational research is precisely what NASA should be doing; in fact, given the limited resources that the ARMD has been allocated, only foundational research is what it can do successfully. In my opinion, NASA's role in aeronautics research should be as a bridge between academia, which conducts fundamental research, and industry which ultimately ensures the preeminence of the United States in aerospace technology. As such, NASA should inspire and support the best minds in this country to carry out fundamental research relevant to aerospace industry. To be an effective bridge, however, NASA engineers and leadership should be of the highest technical caliber, in order to be respected and listened to by both academia and industry. In this regard, Administrator Griffin should be commended for appointing an outstanding technical team at the highest leadership levels of the agency. The Aeronautics Directorate should strive to preserve the technical expertise that remains at NASA, and more importantly, to make a valiant effort to replenish its technical workforce. In achieving this goal, NASA needs this body's help in alleviating some of the administrative constraints it is facing.

2. What are the major technological and competitive challenges facing the civil aeronautics industry over the next ten to fifteen years, and how well does the Aeronautics Research Mission Directorate's program attempt to address them?

The main competitive technical challenge facing the civil aeronautics industry is the projected increase in air traffic capacity in the next 10 to 15 years, and the related performance and environmental issues such as noise and harmful emissions. Progress in these areas is very much dependent on a better understanding of the underlying physical phenomena and the subsequent development of the high fidelity predictive models. What is needed here is increased coordinated foundational research in these areas. Considerable emphasis for research along these lines in the recent NASA Research Announcement (NRA) which solicited basic and applied research proposals, demonstrates that ARMD leadership is clearly aware of these foundational technical challenges, and is taking action to deal with them. The European Union has already taken the lead in devoting substantial resources to multinational coordinated research programs for development of high fidelity predictive tools. In recent times they have been more open in trying new ideas and leading edge technologies. Japan has been sustaining a strong long term research program in aeronautics and especially in high speed flight, and China has recently expanded its research activity in aerospace science and technology. It is noteworthy that both countries have received major contracts from Boeing and in particular, Japan is manufacturing the main wing-box of the Boeing 787, its latest commercial aircraft.

Although it is not directly related to the near term competitive challenges facing the civil aeronautics industry, I believe, ARMD has a critical role to play in the area of hypersonics with application to both manned and robot space exploration missions. Foundational research in physics-based modeling is required for high speed large payload planetary entry, descent and landing. ARMD has the technical means to take the lead in this area, but the necessary resources, in my opinion, should be provided from the space exploration mission.

3. What advantages can be gained by having NASA increase its emphasis on computational- and physics-based modeling? Why should NASA be pursuing this technology? Does NASA have the workforce and facilities to conduct this research?

Computational science has been recognized as the third leg of the stool representing 21st century science, together with theory and experimentation. Computations enable us to investigate phenomena where economics or physical and environmental constraints preclude experimentation (see recent report of President's Information Technology Advisory Committee). The last twenty years have seen the rise of computer-aided engineering in almost every industrial sector. Today, many aspects of product development, design, optimization, performance analysis and certification rely heavily on the use of computations. Computers are also the latest resource available for scientific discovery. Over thirty years ago the visionary leaders of NASA and its highly acclaimed research staff pioneered the development of the discipline of computational aerodynamics and its transition to industry. Today computational modeling is an integral part of aircraft and engine design and is responsible for dramatic reductions in the required expensive wind tunnel and engine tests. However, in spite of its successes, computational engineering is far from being predictive for complex engineering systems. New high fidelity methods, physics-based modeling research, computer science, and validation and verification tools, including tighter coupling to laboratory experimentation are required before achieving predictive status.

Over the past five years alone, the super-computer power has increased by two orders of magnitude. Because of this there now exists new opportunities to conduct high fidelity integrated computer simulations of complex engineering systems. Therefore, NASA is clearly correct to increase its emphasis on computational and physics-based modeling. NASA has invested in super-computer hardware and should continue to do so. There is also a clear emphasis in computational and physics-based modeling in NASA's recently released NRA. However, to reestablish its historical preeminence in this area, NASA needs to retain its existing knowledge base and build on it by carefully complementing and replenishing its workforce with young talented Ph.D. engineers.

A solid experimental program is vital for physics-based model development and validation of computer simulations. NASA should continue to invest in its unique facilities, and should cooperate with universities in small-scale laboratory experiments.

4. What has been the experience, of late, with respect to universities recruiting students into post-graduate aeronautics-related research programs?

There does not appear to be any pronounced decline in the enrollment of graduate students in the top ranked aeronautical engineering departments and in related engineering fields in the U.S. However, a disturbing new phenomenon for NASA is that the agency appears to be a less attractive career choice for most of these highly skilled engineering Ph.D. graduates. Back in the late seventies when I joined NASA, the agency was considered a top, competitive career choice for many of the most talented engineers in the country. They were attracted to the agency for its unique research facilities and for working with, and being mentored by, some of the most illustrious technical leaders in aeronautics. According to the 2005 membership directory of the National Academy of Engineering, only two active employees of NASA's aeronautics field centers have the distinction of membership in the Academy. This is disproportionately low for the country's leading aeronautical research enterprise.

Finally, as you are undoubtedly aware, about one half of engineering Ph.D. graduates in the United States are foreign born. Due to various cumbersome and in my opinion, often unnecessary restrictions given, the current global economy, it is extremely difficult for this technical workforce to be employed by the civil aerospace industry or NASA. I believe, it is in our best national interest to embrace this enormous technical resource and provide opportunities for these U.S. graduates for postdoctoral fellowships in NASA, and employment in civil aeronautics industry and for eventual full citizenship.

BIOGRAPHY FOR PARVIZ MOIN

Parviz Moin is the Franklin P. and Caroline M. Johnson Professor of Mechanical Engineering at Stanford University. He received his Bachelor's degree in Mechanical Engineering from the University of Minnesota in 1974 and his Master's and Ph.D. degrees in Mathematics and Mechanical Engineering from Stanford in 1978. He held the posts of National Research Council Fellow, Staff Scientist and Senior Staff Scientist at NASA Ames Research Center. He joined the Stanford faculty in September 1986. He founded the Center for Turbulence Research and the Stanford's Institute for Computational and Mathematical Engineering. Currently he is Director of the Center for Turbulence Research and the Department of Energy's Advanced Simulations and Computing Center at Stanford. He is actively involved in the editorial boards of the *Annual Review of Fluid Mechanics,* the *Journal of Computational Physics,* the *Physics of Fluids, SIAM Journal of Multi-Scale Modeling and Simulation,* and the *Journal of Flow Turbulence and Combustion.*

Prof. Moin pioneered the use of direct and large eddy simulation techniques for the study of turbulence physics, control and modelling concepts and has written widely on the structure of turbulent shear flows. His current interests include: aerodynamic noise and hydro-acoustics, flow control and optimization, large eddy simulation, turbulent combustion, aero-optics, parallel computing and numerical methods.

He has been awarded NASA's Exceptional Scientific Achievement Medal, NASA Outstanding Leadership Medal, the Lawrence Sperry Award of the American Institute of Aeronautics and Astronautics, the Humboldt Prize of the Federal Republic of Germany, and the Fluid Dynamics Prize of the American Physical Society. Prof. Moin is a Fellow of the American Physical Society and is a Member of the National Academy of Engineering.

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June 16, 2006

Honorable Ken Clavert
Chairman
The Subcommittee on Space and Aeronautics
House Committee on Science

Dear Representative Calvert:

I declare, as requested in your memorandum of January 25, 2005, that I am the Director of the Center for Turbulence Research which is funded through a grant from NASA, and which operates under a memorandum of understanding between Stanford and NASA, signed in 1987. Furthermore, per this memorandum, neither I, nor any other Stanford University Faculty member, receive any portion of their salary under this agreement.

Best regards,

Parviz Moin
Franklin and Caroline Johnson Professor
in the School of Engineering and
Director, Center for Turbulence Research

DISCUSSION

PRIORITIES FOR AERONAUTICS PROGRAM

Chairman CALVERT. Thank you, Doctor.

I have got a couple of questions I want to get the panel on the—views on the record. And this would be for the entire panel, except for Dr. Kaminski.

Do you think that the Decadal Survey proposes a sound set of priorities for the aeronautics program, one. And the next two questions are pretty much the same. Are there any areas where you take exception to this survey, and did the survey miss anything that you think should have been included?

So, Dr. Merrill, I will start with you.

Dr. MERRILL. Well, it would be unwise for a member of the Academy staff to question the results of another Academy study.

I think they have done an excellent job, and I note that some of the emphasis on, also, the other witnesses on the sort of crisis in capacity, and environmental challenges ahead are very high priority.

Chairman CALVERT. Dr. Romanowski.

Dr. ROMANOWSKI. Yes, Mr. Chairman. As I indicated in our statement, we do think, by and large, the Decadal Study is a very good document. It does provide an excellent roadmap with the caveat that there are few areas that we saw as—because of the characteristics of the quality function deployment methodology used, where it didn't emphasize certain areas, if they only ranked into one or two strategic areas, we think that with the addition of advanced avionics technologies, more efficient certification processes, more advanced processes for the complex, software-intensive systems, and secure network center avionics architecture and systems. With those additions, those things that are going to be critical to NGATS, we think that they have a very fine roadmap.

Dr. MOIN. I do believe it was an excellent study. There are a couple of points that I would shift the priorities, or perhaps put more emphasis on. One area is the hypersonics area, which the Decadal Study did emphasize as important. I also feel that it is very important, especially for space exploration, going to the Moon and Mars, and I think the Aeronautics Directorate can play a significant role in this area, but I don't think it has the means and the budgetary resources to be able to do so, and perhaps, some of the funding for this research can come from the space exploration groups.

With regard to the emphasis on disproportionate allocation of resources within the Aeronautics Directorate to the in-house services, I think that the Aeronautics Directorate is, perhaps, between a rock and a hard place in this respect. They have civil servant employees that there are no clear paths of how to adjust the numbers, and therefore, they had to allocate a significant fraction, which I believe, actually, is about 75 percent of their resources, for the inhouse programs.

Chairman CALVERT. Thank you.

NASA PROGRAM RESTRUCTURING

Dr. Kaminski, over the last year, as you know, NASA, that is the reason we are here, has significantly restructured its aeronautics program to focus more, as has been mentioned in testimony, on basic research.

Can you give us your assessment on how the Decadal Survey compares with what NASA is proposing in its own restructured program, and are there any specific areas identified in the survey which NASA, again, has not addressed in this restructured program?

Dr. KAMINSKI. Mr. Chairman, my sense overall here is it is a little soon to tell, because pieces of the NASA program are still being implemented as we speak.

I think I and you would be in a much better position to answer that question in about a year, to see how things are deployed, and how the program is actually exercised. I don't think the scope of funding available to NASA in the President's budget request is going to be adequate to cover the scope that was listed in our 51 prioritized areas.

Chairman CALVERT. During the testimony, Doctor, I am kind of getting out of order on these questions, but it occurred to me, when you were talking about computational advancements over the last number of years, and you know, I read that the, those advancements are going to even go faster in the next number of years. A lot of the infrastructure that NASA has today in wind tunnels, you know, the graph that shows the number of wind tunnel tests going down dramatically, do you believe that NASA should take a very strong look at that cost, that infrastructure cost, that it has, and not only operating those wind tunnels, but maintaining those tunnels?

Dr. MOIN. I think maintaining those tunnels are absolutely essential for the agency. They are unique national facilities, and all of these computational-based studies will ultimately need the wind tunnel tests for validation, especially——

Chairman CALVERT. So, even though the efficiencies, in effect, if you are not operating a piece of equipment as often as you used to, your operational costs per hour, by definition, will go up, but you still need—you are stressing that you still need to maintain that infrastructure, in order to validate the computational——

Dr. MOIN. Correct. Correct.

Chairman CALVERT.—evaluations that you are coming up with.

Dr. MOIN. Precisely, yes. The energy cost, energy input, of course, will not go up, the power required for these, but the manpower required to keep the staff to maintain them, yes, will stay constant, even though the number of tests eventually will go down. But the number of tests particularly will go down for industry. These facilities are, I think, always, usually are booked solid anyway, and we will always need them for validation of the computational models.

Chairman CALVERT. Thank you. Mr. Udall.

Mr. UDALL. Thank you, Mr. Chairman.

NASA RESEARCH PRIORITIES

Again, I want to acknowledge the panel, and the great insight you have brought to the committee today.

I mentioned in my opening statement that I think NASA needs a vigorous program of basic research, and I think all of you agreed in your testimony. However, one of the messages that I take away from the two National Academies reports, as well as from Dr. Romanowski's testimony is that while basic research is important, NASA can't limit its aeronautics program to just basic research if it is going to make real progress.

Dr. Kaminski and Dr. Merrill, is that a correct interpretation of what your reports are saying?

Dr. KAMINSKI. From the Decadal Survey, yes. Our assessment is we need some balance across the timeframes from basic research to occasionally be able to do some demonstrations of the integration of the technology. Where the rubber meets the ramp, when you actually have to build something, and verify and validate the tools that you are developing. That has to be done from time to time.

Mr. UDALL. Dr. Merrill.

Dr. MERRILL. The answer is yes, and I think important to emphasize that from somewhat different perspectives. The Decadal Study, from a very detailed look at NASA's portfolio, and ours, from a more ten thousand foot level look at the capabilities of, and economic incentives that apply to the potential users of NASA technologies.

Mr. UDALL. Dr. Romanowski, would you care to comment?

Dr. ROMANOWSKI. Yes, thank you, Representative Udall.

Yes, obviously the basic, fundamental, foundational research that NASA does is important, but there is this, there is a broad gap between that foundational research that can be done, and being able to make business case decisions on how to implement that technology, or whether that technology is able to be implemented.

And there is, as Dr. Moin indicated, there is a bridge that needs to be built, and that bridge is the transitional research, and that is where we feel, that is a critical portion of what NASA needs to do. That comes from a variety of areas for implementing capabilities. There is potential for supersonic civil flights, but there needs to be work done to establish a baseline for regulation and noise perception for the types of aircraft that would be able to fly supersonically without a sonic boom.

There are also research that needs to be done, if we look at NGATS, there is a lot of work being done by NASA on the fundamental side of air traffic management, but before systems can be developed and built that use the 4D trajectory modeling and that sort of thing, there has to be validation of those capabilities before, and you need to be able to set standards to design and build those systems and certify those systems before they can be put into use, so that transitional research, that bridge between the fundamental and the product, need to go, needs to be done, or else we won't be able to implement those technologies.

Mr. UDALL. Dr. Moin, if I might just re-characterize my question. You seemed to be, at least from my interpretation, saying that NASA should limit its aeronautics programs to just basic research.

If so, would you respond to what the other witnesses have shared with us?

Dr. MOIN. My statement, given the current resources, and limited resources, I think that is essentially all NASA can do. In an ideal world, if NASA had twice its allocation, financial allocation, yes, it could engage into successful demonstration projects as well.

My other comment is usually organizations, and this was the case, I think, in the past, and I used to be at NASA, engage in both fundamental, the entire spectrum, fundamental to demonstration. At times of tight fiscal policy, it is the fundamental parts that gets cut first, because of the need to push the technology and deliver to the customer at that point.

Mr. UDALL. I hear you saying then, you look at the research dollars available, you look at the portfolio NASA could embrace and implement, and you are setting priorities. If you had additional resources, I don't hear you suggesting that we shouldn't do more of this transition-oriented research and development.

Dr. MOIN. Absolutely, yes.

Mr. UDALL. So, you would be supportive of that.

Dr. MOIN. Yes.

Mr. UDALL. But you are saying the world, this is how the world is, not how we want it to be, and this is how you would like to see us focus our——

Dr. MOIN. Yes, and the highest priority would be—if the budgets are tight—the highest priority would be foundational research. I always feel that NASA's responsibility ultimately is to the future generation of Americans, to the taxpayers, and secondary, of course, to the economy, and help the industry.

Mr. UDALL. I assume my time is expired, but I would note that there are others who would say well, we still, in this constrained resource environment, have to do more of the transitional work somehow, but your point of view is well considered, and thank you for your time.

Chairman CALVERT. Mr. Rohrabacher.

POLICIES TOWARDS CHINA

Mr. ROHRABACHER. Thank you very much. I would just like to take maybe a different approach, and see what the panel would say.

Where does decisions, or where do the decisions that we have to make, in terms of industrial decisions that we have to make in your future play into this? For example, Boeing, I understand, is right now involved in making a determination whether or not that they will be partnering with China on this.

It seems to me no matter what we do, in terms of financing at the Federal Government level, that a decision as fundamental as that is way beyond what we are talking about, in terms of the importance of what this industry will look like in 10 to 20 years. I personally would go on record to say that I will do anything that I can to stop the partnering with China that will result in a Chinese aerospace industry ten years down the road, simply for short-term profits today. There is no reason for our country to sell out future generations, simply to get us over a hump today.

And I would like to ask the panel's response to that. Don't all jump at one time now.

Dr. ROMANOWSKI. I will start. I will start by saying, Mr. Rohrabacher, that I think there are a lot of issues that go into those kinds of decisions, and sometimes, those decisions are driven by availability of technology. Sometimes, they are driven by market access.

I think increasingly in the future, we are going to see some of those decisions driven by the availability of suitable talent, which is why I come back down to the importance of being able to develop affiliations with universities, supporting a diverse research aeronautics base in our universities in the country, creating an exciting environment for those graduate students that——

Mr. ROHRABACHER. You may well be right in the future, but that is not what is right today. What is right today is they are making deals for market access, and everybody knows that, and if we keep, of course, educating Chinese young people, so that they can go back and out-compete our young people, maybe in the future, we will face that. The fact is that Chinese graduate students are getting a better education than our own young people, and get, actually, more support overall from their society, than do the young people who go into engineering at graduate levels in our society.

But right now, Boeing is talking about setting up manufacturing units in China, in order to have access to that market. And you are right, maybe in the future, we may end up, if we don't watch out, having to have partnerships with these countries based on skill. Right now, we have the skill, but would—are you folks generally supportive of partnerships with, especially, countries like, well—China is not a democratic society. I am opposing this because China is a non-democratic society, and could well be our adversary, but what is your general reaction to that idea of partnering, and thus, setting up competitive situations overseas?

You are shaking your head down there, so maybe you would like to——

Dr. MOIN. Well, Boeing is a global corporation in a global economy, and I think they make business decisions, how to handle it. We are—I do not how the government can interfere with that. It is their business decision to do so. Do I support it or not? That is something I have to think about. I mean, for example, as I mentioned in my testimony, Boeing just granted the construction of the wing-box of 787, which is really, if you talk to some Boeing engineers, they call it the crown jewel of their airplanes.

Mr. ROHRABACHER. Correct.

Dr. MOIN. To Japan.

Mr. ROHRABACHER. At least Japan is a democratic society.

Dr. MOIN. Yes.

Mr. HONDA. It wasn't before.

Dr. MOIN. It was not before.

Mr. ROHRABACHER. No, it wasn't before. I hope we don't have to go through the same thing with China in order to get it there.

Mr. HONDA. Well, if the gentleman would yield for a second, you talked about long-term versus short-term, if we are looking at long-term, in the context of what we are looking at today in our own country, I don't think our witnesses have said it, but what I am hearing all the way through this testimony is we ain't got the money, and since we ain't got the money, we got to make choices that are difficult, between NASA research, long-term research, and that has, in itself, impact on education——

Mr. ROHRABACHER. Well, reclaiming my time for one moment.

Mr. HONDA. Sure.

Mr. ROHRABACHER. I will say once, and I know you have been here a while, but I have been here 18 years, and it is always the money. It is always the money, the money, the money, the money, and that is not what it is all about. The fact that there are major decisions made by leaders in industry and in government that are not just monetarily driven, that have huge impacts on our competitiveness, and on the direction of our industrial infrastructure, and our ability to succeed in the future.

Partnering is one of them, and who we partner with is one of them. And so——

Chairman CALVERT. The gentleman's time has expired.

Mr. ROHRABACHER. Yes, thank you very much.

Chairman CALVERT. Mr. Honda, you are now recognized on your own time.

Mr. HONDA. Thank you.

Picking up on that, partnering is, it seems to me, based upon profits and how we can make do with what we have got, and maybe I haven't been here eighteen years, but using my friend from California's phrase that I really love. I hate to be the skunk in the garden party. Look, I am just going to say, you know, it boils down to our fiscal portfolio that we put out there, because these kinds of discussions were not a debate when we were moving forward in a very fiscally responsible way, and now, we are asking the gem of our country, NASA Ames, to make a choice whether we should have A in NASA or S in NASA, when NASA should be complete, and move forward.

And so, I think, in the words of Pogo, you know, we have seen the enemy, and he is us, you know, and I think we need to look at our own way of how we do business before we, as we move through this, and reconsider how we do business in this country, and how we run our own ship, and I think that if we do that properly, we won't have testimonies like this. Rather, we would be talking about how well we can take advantage of foreign students, and they would become our citizens. If you come to Silicon Valley, 10 percent of our CEOs are foreign born, and yet, they stay here, and got their citizenship, and created thousands of jobs, and been the economic engine and the innovative engine of our country, if not of this world. And we all benefit from it, and I think we can learn from this whole thing, what we call it, globalization now.

We are a country of diasporas, and we need to take advantage of that for the benefit of our future, and if we don't take care of those kinds of basic things here in this country now, then we shall pay the penalty in the future, and as my friend said, you know, we have some serious concerns about our, the folks across the ocean, and we should. We should not be naive, but at the same time, we can model as we partner with them, and have certain expectations of them, as well as ourselves.

So, I invite the challenge, but I think that to ask questions about, you know, what should we, what is the priority, and have them make those difficult choices, is maybe a fair question, but it is a question that is necessitated by our own fiscal shortsightedness.

And I appreciate the chairman's indulgence, and my colleagues' indulgence, and it is not that bad to be a skunk at the garden party once in a while. And I thank my friend from California for teaching me that phrase.

Chairman CALVERT. Thank the gentleman. I would point out, in the NASA budget, even though in our authorization budget that all of us worked on, which unfortunately is not being funded to the same level during, as you know, in the appropriations process, every aspect of NASA has been cut, including the exploration budget. One of the reasons the CEV is not going to be online by 2012 is because we don't have enough money in the exploration budget, so we may have as much as a two to four year gap. Hopefully, the gap is not as long as we had during the Apollo-Gemini period, but it is still a gap there, and aeronautics certainly take a cut, science has taken a cut.

And as you know, the Senate bill has requested an additional $1 billion, in their allocation, and you know, I am a fiscal conservative, but as you know, all of us have been here a long time, NASA has been flat-lined during the, in the '90s had a zero increase, and so, in real expenditures, really took the biggest cut of any, probably any agency in the Federal Government, outside of possibly one other aspect of government.

So, I think we really need to take a strong look at this, and as we move through this appropriations process, because I hate to see exploration and science and space fight one another, because that is not going to get us anywhere. We are all going to end up being net losers in that process. So, we need to work together to try to increase the top line allocation, in order to make sure that we maintain our superiority.

And with that, Mr. Forbes, you are recognized for five minutes.

AERONAUTICS BUDGET

Mr. FORBES. Thank you, Mr. Chairman.

I would like to follow up on some of the chairman's comments. They always say to go to a car lot and try to look at a car, and not be able to figure out the price and what it is going to cost. And if you look at three reports, the *2002 Aeronautics Blueprint, 2002 Report of the Commission on the Future of the U.S. Aerospace Industry,* and the *2005 National Institute of Aerospace* report, as I understand those reports, they basically conclude that U.S. competitiveness in the aerospace industry is in jeopardy without a substantial, long-term, sustained investment in aeronautics research, and Dr. Kaminski and even the Decadal Survey of Civil Aeronautics makes some recommendations to accelerate NASA's aeronautics program. I would conclude, basically, that you, as a panelist, don't feel that the 2007 budget for Aeronautics Research Mission Directorate responds adequately to the conclusions presented in those reports.

My question for you is this. If the NASA Authorization Bill is directing the Administration to develop a national aeronautics policy by the end of this year, to guide NASA's aeronautics research program, my question is what kind of investment will NASA have to make in the coming years to ensure that this policy, whatever it comes out to be, is a blueprint, rather than just a wish list. Any idea of the kind of investment we are looking at?

Dr. KAMINSKI. Mr. Forbes, since our committee didn't, was not chartered, in fact, we were asked not to make budget recommendations. I can't speak for the committee or our study. I can speak personally.

Mr. FORBES. What I am asking.

Dr. KAMINSKI. And from a personal perspective, I think it is important to keep in mind two other issues before I comment on level of funding. Stability of funding for this kind of activity is extremely important, so I could not recommend a program that made a 20 or 30 percent increase in one year with the expectation that we might not have it next year, or one wants to build a stable foundation, because you can't control the people and the education and the infrastructure by just turning a knob. This takes a few years to absorb, and a few years to wind down, and so, that stability is key.

There is also a need for a balance in this program, a balance between internal expenditures at NASA and external expenditures. We want to bring our universities into the program. We want to bring industry into the program, for transfer, and also, for the statement of needs. So, that interaction is very key. There also needs to be a balance, as we have spoken about, in terms of underlying research base, and demonstrations from time to time, to be able to actually build some things, and see whether they prove out, the research underlied that pace.

If I look to see what kind of program funding is required to make a reasonable cut at what is in this decadal program base, my own sense is that it is about the twice the budget that we are working with me. That is just a personal opinion.

Chairman CALVERT. I thank the gentleman. Ms. Jackson Lee, you are recognized.

FUTURE OF NASA

Ms. JACKSON LEE. As always, I would like to thank the Chairman and the Ranking Member of the Subcommittee, Chairman of the Subcommittee, for their timeliness and innovativeness on these hearings.

I do want to acknowledge the witnesses, as well. I am going to take my time to really focus on NASA as a whole. This is particularly timely, inasmuch as we face, this hearing, at the backdrop of a very successful Shuttle, if you will, launch, and now, reentry. And certainly, questions were raised as to whether or not that was even possible.

I think that the discussions, the thrust that the focuses that we have had, or the focus that NASA has had, have done somewhat of a disservice to civil aeronautics is probably true. And certainly, it is not only a question of vision, but it is a question of resources, and we would be disingenuous if we did not indicate that much of what has been probably discussed is the lack of money, because when the President announced about two years ago the focus on the Mars mission, it was with great fanfare and enthusiasm. And we also know that research and space exploration also adds to civilian better quality of life.

But choices had to be made, and so, it took and takes billions of dollars to have an effective space exploration program, and you shortchange research, you shortchange focus on civil aeronautics, you shortchange basic science. All of these are valuable assets or parts of the NASA program that have now been shortchanged. So, I think this hearing really should be about adding not only to the vision, but to the resources, so that the words of the witnesses could be emphasized.

I happen to be celebrating the new culture of safety that has occurred at NASA. Interestingly enough, there was great debate and some drama, right before Discovery launched, the disagreement between safety engineers, the overriding of their decision by the Administrator based upon his, in his viewpoint, thorough vetting, but even that airing of disagreement had never occurred before, to my knowledge, at least in my tenure here in the Congress, and probably would have saved some lives of the individuals who lost their lives in Columbia, if there had been that kind of vetting.

Interestingly enough, as it launched, and I met with the Administrator in my office just the day before he went down to Kennedy, and talked even more about these issues, but we saw, even in space, the detailed review of the Shuttle, to determine whether any damage had occurred, something new, and as well, the cautious review to whether or not we should reenter, and of course, adding weather conditions and otherwise.

That should be celebrated. So, I don't want to see the idea of a vision to underestimate the importance of a new attitude at NASA as we coax through a blueprint or an expanded blueprint for NASA. My thoughts would be that we need to focus, if you will, on finding the resources, so that we can be complete in NASA's mission.

Aeronautics and the Vision

With that in mind, I would like to just ask this general question for all to answer, and that is, do we have the sufficient grounding for celebrating improvements that NASA has made, and do we need a vision without funding? Isn't funding a crucial aspect to any expanded vision and any expanded emphasis on civil aeronautics?

Chairman CALVERT. Any gentleman can answer that question.

Dr. ROMANOWSKI. Can I answer it, or jump in, please? Thank you, Mr. Chairman. Thank you for the question, Representative Jackson Lee.

You are right. Implementation of the Vision in NASA is integrally tied to the funding at NASA. Right now, the NASA aeronautics program is facing a 20 percent budget cut for the coming year, if no changes are made by the Congress. It is very difficult to implement the types of research that we believe are necessary, and that are not only necessary for the health of NASA, for the health of our universities and industry, but also, the health of our economy.

You know, if we look back several years, pre-9/11, we look at the news, the news was entirely about the lack of capacity at our airports, and the disruptions and delays. We are seeing a lot of that now in the summertime, because capacity is where it was back then. We haven't made the improvements, and traffic is back at pre-9/11 levels. We know, unfettered, the growth in traffic would triple over the next 20 years here in the United States, but right now, we are faced with implementing, we need to develop and implement a new next generation air transportation system that can accommodate that growth. That takes resources.

As I mentioned in my statement, the current estimates, preliminary estimates that we are hearing indicate $200 to $300 million per year for transitional research are necessary to implement those changes, and those are not just critical for NASA. They are not just critical for industry. They are critical to our economy, because our economy is continually more dependent on aviation and services provided by aviation. So, it is something we need to do. Thank you.

Ms. LEE. Anyone else? Anyone else want to comment on whether safety improvements have been a positive step for NASA?

Dr. MERRILL. I am sure they have, but I wanted to address your general point about whether an increase in resources is necessary to achieve an expanded vision for NASA aeronautics, and I think the panel has unanimously agreed that that is the case, and probably, that increased resources are needed to even maintain the mission of NASA aeronautics, as diverse as it has been over the years, going forward.

Now, the—I guess the encouraging thing about the last couple of years is that NASA has recognized that it can't do everything, and that it, and to continue to do everything, they have spread resources too thinly, they have stretched out projects too long. And it is somewhat unsettling that the result, within a single Administration in the last two years, has been a slimmed down sort of focused vision, that is much more—that is so diametrically different, as the plan to revamp the vehicle systems program two years ago, compared to the focus on fundamental research today. But at least it is encouraging that NASA is presenting realistic options for Congress to consider.

But I think the answer has to be that to do what any number of commissions and panels have recommended that they attempt to do is going to require considerable additional resources.

Chairman CALVERT. Thank you. The gentlelady's time has expired.

Ms. LEE. I thank you. Thank the witnesses very much.

AERONAUTICS PRIZE

Chairman CALVERT. I would like to ask a couple of questions.

One, Dr. Merrill, very quickly, one of the key recommendations in your report was that NASA offer a high profile aeronautics prize. From my history class, Charles Lindbergh, you know, flying to Paris to receive the $25,000 prize he received in 1927. I don't know what comparable number that would be today. But what challenges do you think are appropriate, to pursue under a prize program? Do you think that is worth doing? Obviously, you do, but what goals would you put out there?

Dr. MERRILL. I am not sure. I would leave that to the technical experts on the panel and elsewhere to suggest candidates, but my program is currently engaged in a study for NSF to implement fiscal year 2006 appropriations directive to establish an innovation prize. I think we have become convinced that it is a useful, important, and in many cases, successful instrument to promote innovation, and that it is unfortunate that NASA has chosen to concentrate its attention for the challenge prize on Space Exploration.

Chairman CALVERT. I agree with you. I like incentives, and I think if they are set right, that there are folks out there that still work in their garage, and come up with some fantastic inventions. I also want to ask for the panel. I am also on the Armed Services Committee, and deal a lot with issues that we are dealing with in our military, and I deal closely with DARPA.

Do you think that it would appropriate for NASA to have a DARPA-like program, in order to pursue projects that are kind of cutting edge? And I will start on this side here, with Dr. Moin.

Dr. MOIN. Well, in addition to what they have right now, yes.

Chairman CALVERT. Yes, I am talking about in addition to.

Dr. MOIN. Yes, I think——

NASA AND MILITARY RELATIONSHIP

Chairman CALVERT. And I will also ask the question, by the way, just to kind of tie that in, how well does our civil aviation program work with our military? It used to be, years ago, that NASA had a very close working relationship with the Department of Defense. Some people argue that that is not nearly as close as it used to be, so you might just kind of tie that. Do you believe that to be the case, or do you think that is changing?

Dr. MOIN. I think, given the fact that the research done in NASA are mostly unclassified, and the research in the DOD side are classified. I think, given that fact, still I see a lot of interaction between them, certainly in the fundamental research areas, as the Decadal Study also indicated.

In physics-based modeling, computational engineering, there is a lot of crosstalk, combustion research, propulsion, there are different areas of interest. For example, military is not necessarily interested in emissions and noise at the airports, but NASA is, and vice versa. NASA is not necessarily interested in afterburners for the propulsion system, et cetera.

But in the areas of common interest, like aeronautics, like supersonic, subsonic, hypersonic, there are many areas of overlap that I think there is a very good collaboration, especially in the foundational research areas.

Chairman CALVERT. Anyone else on the panel like to add to that? Dr. Kaminski.

Dr. KAMINSKI. With respect to cooperation with the Department of Defense, I think there is a lot of room for productive work there. I go back three careers back for myself, when I was serving as an officer in the Air Force, and I served for several years as Director of the Stealth Program, got enormous benefit from, support from NASA to that program, with the challenge of building the very best antenna that we could build, and then every now and then, to see if it would fly. Well, the NASA wind tunnels and aerodynamic experience base were very helpful to us. And simply because of the reduced scope of the program, there is less of that going on today.

Chairman CALVERT. Yes, Dr. Romanowski.

Dr. ROMANOWSKI. Yeah, well first off, on the subject of whether DARPA, or NASA should have a DARPA-like capability, I think that should be something that should be explored, as Dr. Moin said, not a replacement for what NASA Aeronautics does, but maybe an augmentation of their capability, that should be explored and looked at. In terms of their relationship with DOD, in the past, it has been very good, but over recent years, from what we have seen, that engagement was discouraged, in many respects.

What we are seeing, though, is over the time, the recent advent with the coming of the JPDO, with the coming of the national aeronautics policy, you are starting to see a little bit more movement back towards cooperative arrangements between NASA, FAA, DOD, on various activities, and that is something we believe is very healthy, because there are a lot of synergies amongst the various government agencies that can be taken advantage of, both for civil taking advantage of military technology, and military taking advantage of civil capabilities.

Chairman CALVERT. Thank you. Mr. Udall.

Mr. UDALL. Thank you, Mr. Chairman.

FUTURE DIRECTION OF NASA AERONAUTICS RESEARCH

The three of you, or maybe Dr. Moin, you as well, I don't want to exclude you, and you will have a chance to comment. But you seem to be saying that we need to take our research and technology initiatives to a higher level of maturity than would occur if NASA were just to focus on basic research. I know we keep drilling into this topic, but I think this is really the focus of the hearing, at least from my point of view.

If so, how do we do this? Is it—for example, flight test demonstrations, or prototype development, and do you have in mind a fraction of what the overall NASA aeronautics budget could be devoted, such technology maturation efforts? And maybe we will start with Dr. Kaminski.

Dr. KAMINSKI. I certainly may think it makes sense, in a balanced program, to be able to move concepts from the research phase to technology demonstration phase, and a component or a subsystem demonstration level from time to time. Those aren't hugely expensive. Where the cost starts to go up very dramatically is if you get to a flying prototype aircraft.

And so, even with an expanded budget, along the lines that I was discussing, you will not be able to be doing a prototype aircraft program like that every year. It will be a couple of year process in between, and you have to phase some of the other component or subsystem demonstrations in such a way that perhaps you have a couple of building years where you demonstrate some of those, then you believe you have enough things together to tie them together and do a flying prototype.

But if one assembled an integrated program to be doing that on a routine basis, I believe the kind of doubling of resources I was talking about would make that possible on a sustaining basis, and

I would also expect to see some cooperation, in terms of some industry funding on a partnership basis in some of those activities.

Mr. UDALL. But Doctor, you are suggesting perhaps if we turned and headed in a different direction here, industry would see the opportunity, and a reason to perhaps put some of their resources into——

Dr. KAMINSKI. They might share some——

Mr. UDALL.—join and do——

Dr. KAMINSKI.—some funding in that base, and in turn, benefit from some of the NASA test facilities that are available.

Mr. UDALL. Dr. Merrill, would you care to comment on my initial question?

Dr. MERRILL. I can't be more specific than that, but I think that makes a lot of sense.

Mr. UDALL. Dr. Romanowski.

Dr. ROMANOWSKI. Okay. Yes, thank you, Representative Udall.

First, the flight demonstrations, we believe, are extremely important, and we look at that right now, it is our understanding that some of NASA's flight test capabilities, for example, their 757 flying testbed, are in jeopardy under the current framework. Those things are important. They allow testout of advanced capabilities in the airspace.

In terms of a percentage of the budget, in terms of the near-term, I think we would say that that percent, we are looking at, if we took the $724 million that is currently proposed by NASA for fiscal year 2007, and if that level were restored, that would account for a 20 percent budget that would account for these demonstration or transitional research. We think that is a good starting point. As we move forward, and build a more healthy NASA aeronautics program, based on an integrated national aeronautics policy and the like, that could grow over time, but certainly, that type of number is a good starting point, particularly in light of the shortfalls we know that exist for NGATS.

Mr. UDALL. If the panelists want to comment after the hearing closes today, I am sure we will keep the record open, and I know catching you with a question about a number is maybe something you didn't necessarily plan for, but if each of you would like to look at that, and make a recommendation. I would certainly appreciate it.

Dr. Moin, I didn't want to isolate you from the other three, and I think you did, you and I did have a conversation in regard to this earlier, but if you wanted to comment——

Dr. MOIN. Yes.

Mr. UDALL.—as well, I would be happy to hear what you have to say.

Dr. MOIN. It is my understanding that the grand total money that NASA, through this recent NRA, National Research Initiatives, has allocated is $50 million, to all the universities and small companies. That is discretionary money, in my opinion, after paying for the civil servant workforce and the facilities the NASA Aeronautics Directorate has, $50 million to support all the universities for the fundamental research, and small companies.

Mr. UDALL. I see my time has expired. I might ask the Chairman to include in the request for further information from the panel, particularly Dr. Kaminski, because you spent too much time, and have such a comprehensive sense of what faces us.

And the question would be this, what specific measures can Congress use to determine whether NASA has a successful and relevant aeronautics research program. I think it would be very useful, I know, to the Chairman, to me, and other Members of the Committee.

Again, I thank the panel. This has been very, very informative today.

Chairman CALVERT. I would advise my friend that I would ask Members that are going to submit additional questions to do so within a week, and we will allow our witnesses to answer those questions in writing, and to add that to the record, so, for some follow-up.

ROLE OF GOVERNMENT IN AERONAUTICS

Mr. Rohrabacher, you have one last round of questions.

Mr. ROHRABACHER. Yes, sir. Thank you very much.

Mr. Chairman, let me just note that I respect the fact that what we are talking about here, and what your focus was is basically on NASA's role on American aeronautics competitiveness, and not just an overall approach. But I think that we need to make sure that we keep these things in perspective.

Like I say, that whenever we tend to focus too much on the government agency, we tend to just think more money is going to solve a problem. And quite often, not just in this area, but other areas, we find that more money does not necessarily mean better performance. And more, in terms of what we are talking about today, mean more competitiveness.

I remember very well the same debate, and the same, you know, set of hearings on the same topic of American competitiveness in aeronautics 10 years ago, and at that time, the big issue of the day was not what it is today, and if we take a look today, what we have is the French and the Germans, and I guess the English, too, but I think it is just the French and the Germans with the Airbus, have their A380. They made that decision. They have come forward now to compete with us, Airbus, in a big way they have expanded in the last ten years.

However, it appears to me that they have made a fundamental wrong decision of what direction to go. With all of their subsidies, and with all of the French and German government involvement in Airbus, I am predicting that the Boeing 787 is going to just outcompete them and leave them in the dust. And in fact, we will be, emerge from this competitive situation with Airbus, we will emerge as the victors in this competition, and we will remain, again, the premier aerospace power in the world, but not because of spending by NASA. Maybe number one, because of good judgment on the part of Boeing Corporation, which is, of course, may be perhaps in a different relationship with our government than is Airbus with their governments, which may lead them to bad decisions.

We also, just let us note, that we have a lot of cooperation with the Defense Department, and maybe that gives us an edge, as compared with the French and the Germans, in developing their aeronautics, and their commercial aeronautics, but let me add a couple other factors here, just for the record, so when we talk about the issue of competitiveness, it is not just whether NASA spends more money, but for example, the patent systems in Europe is totally different than the patent system in the United States. Now, let me note that the big companies have tried to change our patent systems, so that it more reflects the European and the Japanese model, which I believe would be enormously harmful to our country's production of new and innovative ideas, but that is something that has to be thrown in this.

And also, Mr. Chairman, let us not forget the general economic policies of our government as a major factor in whether we are competitive in areas like aeronautics. We have a system in the United States Government that we have policies in place that we Republicans can be very proud of, that permits corporations to prosper and to succeed, and not just corporations that are anointed by our government, as is Airbus in Europe, but a lot of corporations have the same policies, and are not just anointed to a few, as is the policy in Europe all too often.

So, let me just note there are other factors involved here, instead of just NASA spending, although I think that some of the points made about making sure that we maintain NASA's ability to help in joint technology development, and in, and for example, testing facilities, et cetera. There are very good points, and we need to make sure that those testing, that testing apparatus, and our ability to partner with our technology corporations, we shouldn't let that just go down and be depleted over the years.

So, I appreciate this hearing, and appreciate your guidance. Thank you very much.

Chairman CALVERT. As always, I thank my friend from Southern California, adjoining district, for his commentary and good questions.

I would like to end this hearing by saying I would, we were both raised in Southern California, and the aerospace industry, when I was a kid, it was basically oranges and aerospace. Maybe Hollywood——

Mr. ROHRABACHER. My dad worked for Northrop.

Chairman CALVERT. Yeah, yeah. There was a little bit of Hollywood in there, maybe, and now, it is—the oranges have gone away. God knows where Hollywood is, there up in Canada someplace, so they are still around.

But the aerospace industry is still around, too, but there is not the same industry as it used to be, but it is still an industry we are very proud of in this country, and one that we actually export a lot of products still. And we would hope that it stays competitive for the next number of years.

Happily for Boeing, they made the right decision on the 787. I was on their mockup yesterday, and I was on the 380 yesterday. It is a big airplane. I just kept thinking how long will it take to load it, and how long will it take to unload it, for those of us who have to fly all the time. And—yeah.

Mr. ROHRABACHER. With that plane, it could go on for days.

Chairman CALVERT. Yeah, and we will be there by the time they get through loading the airplane.

But again, I want to thank our witnesses for attending today. I am sure you will be getting some additional questions in writing. We certainly appreciate your patience.

This hearing is adjourned.

[Whereupon, at 4:02 p.m., the Subcommittee was adjourned.]

Appendix 1:

Answers to Post-Hearing Questions

ANSWERS TO POST-HEARING QUESTIONS

Responses by Paul G. Kaminski, Chairman, Steering Committee, National Research Council's "Decadal Survey of Civil Aeronautics"

Questions submitted by Chairman Ken Calvert

Q1. Key Barriers to Objectives: You have highlighted two key barriers that must be overcome before the objectives in the Decadal Survey can be accomplished. These barriers are: (1) the certification process for new technologies; and (2) managing changes resulting from inserting new technologies into complex systems, such as the air transportation system. Can you expand on why these two barriers are so critical and the ramifications if they are not adequately addressed? To what degree does NASA's current program address these barriers? What recommendations do you have for activities that would address these barriers?

A1. The first and third question can both be addressed in excerpts from the Decadal Survey report:

Certification

Certification is the demonstration of a design's compliance with regulations. For example, before it can be operated by U.S. airlines, a new aircraft must be shown to comply with U.S. federal aviation regulations. As systems become more complex and non-deterministic, methods to certify new technologies become more difficult to validate. Core research in methods and models for assessing the performance of large-scale systems, human-interactive systems, non-deterministic systems, and complex, software-intensive systems, including safety and reliability in all relevant operating conditions, is essential for NASA, because such research is currently beyond the capabilities of regulators such as the FAA. The ultimate utility of this research will be significantly enhanced through early and consistent coordination of technology maturation with the FAA and other organizations responsible for certification of operational systems. Furthermore, this research would be facilitated by collaboration with other organizations involved in advanced software development methods.

Certification can also be a major barrier to the ultimate implementation of new technologies and operating concepts. In some cases, such as low-cost avionics for general aviation, the cost of certification can be several times greater than the cost of developing and manufacturing the product itself. Furthermore, relying on empirical testing to demonstrate compliance with certification standards may not feasible for large-scale systems (including complex, software-intensive systems and air traffic operating concepts) and human-in-the-loop behaviors, which are not the same in different operating contexts; in these cases, certification will be substantially aided by the use of design tools and design processes developed to mitigate concerns about design validity, safety, and reliability. Certification issues can be showstoppers if not addressed early in the R&T process. Thus, NASA should address the following concerns in its aeronautics R&T program:

- Systematic documentation and publication of model and design assumptions from the earliest stage of R&T development, to aid in a technology's ultimate certification.
- Ongoing iterative validation of models and design tools—and their specifications—during their development, and verification of models and design tools relative to their specifications.
- Generation of databases and models from empirical data to provide a basis for validation and certification.
- Establishment of community-accepted metrics, criteria, and methods for validation and certification, to include principles of "design for certification."

Recommendation 4. NASA should support fundamental research to create the foundations for practical certification standards for new technologies.

Change Management, Internal And External

The air transportation system includes large organizations with long-standing institutional cultures and business concerns that are impacted by—and sometimes resist—the introduction of new technologies. These organizations must be motivated to participate in new operating concepts and to accept the risk of change to improve performance. Changing an interactive system as complex as the air transportation system is difficult because it involves changing a large number of individual elements, including equipment of many different kinds, personnel training, institutional organization, and business models. Additionally, the end state of the air transportation system remains undefined, so R&T should create and maintain the flexibility to steer the system in any of several different directions. This requires interdisciplinary applications of large-scale systems engineering, organization design, economics, and financial analysis, an approach which in some ways is beyond the current state of knowledge. Even so, improved change management techniques are vital to a cost-effective, non-contentious, and safe transition to the air transportation system of the future.

Change management within the Federal Government is particularly important because of the major impact that federal agencies, regulations, and funding have on the operation of the air transportation system and the development of new aeronautical technologies. In addition, change management within the Federal Government is particularly difficult because of the complex internal organization of the Federal Government, with multiple independent agencies, competing national priorities, and political factors that are beyond the control of any one person or agency. One way to facilitate change in the midst of such complexity is to establish strong, focused leadership that establishes a public/private process for change that defines air transportation as a national priority, produces a widely endorsed long-term vision of the air transportation system, and coordinates action by interested organizations. The process should be carefully structured to accommodate the increasing complexity of the air transportation system, competing national and organizational priorities, and fiscal limitations. The process should produce validated R&T requirements, a clear understanding of government and industry roles, and a plan to implement new technologies, operational concepts, and system architectures.[1] The establishment of the Next Generation Air Transportation System (NGATS) Joint Planning and Development Office (JDPO) is an example of federal efforts to change inter-agency relationships to improve change management in civil aviation.

The issues related to change management transcend NASA's role as a single agency. The Federal Government should continue to support the work of the JPDO while conducting a high-level review of organizational options for ensuring U.S. leadership in civil aeronautics.[2]

Recommendation 5. The U.S. Government should align organizational responsibilities as well as develop and implement techniques to improve change management for federal agencies and to assure a safe and cost-effective transition to the air transportation system of the future.

Since NASA's current program has not yet been released, we are unable to comment on the degree to which they address these two Key Barriers.

Q2. External Community: From your perspective, has NASA done a good job of reaching out to its stakeholders, customers, and partners in developing its plans? What do you recommend NASA do to improve those relationships?

A2. Two recommendations confirm the importance of reaching out to stakeholders and involving them in the planning *as well as the implementation* of NASA aeronautics R&T, as follows:

Recommendation 6. NASA should ensure that its civil aeronautics R&T plan features the substantive involvement of universities and industry, including a more balanced allocation of funding between in-house and external organizations than currently exists.

Recommendation 7. NASA should consult with non-NASA researchers to identify the most effective facilities and tools applicable to key aeronautics R&T projects and should facilitate collaborative research to ensure that each project has access to the most appropriate research capabilities, including test facilities; computational models and facilities; and intellectual capital, available from NASA, the Federal Aviation Administration, the Department of Defense, and other interested research organizations in government, industry, and academia.

[1] National Research Council (NRC). 2003. *Securing the Future of U.S. Air Transportation: A System in Peril.* Washington, D.C.: The National Academies Press. Available online at *http://fermat.nap.edu/catalog/10815.html*

[2] A more detailed assessment of the management and organizational issues associated with NASA aeronautics R&T appears in another recent report, *Aeronautics Innovation: NASA's Challenges and Opportunities.* NRC. 2006. Washington, D.C.: National Academies Press. Available online at *http://fermat.nap.edu/catalog/11645.html*

However, the scope of the report did not include evaluation of NASA's plan development, or the way in which it includes other stakeholders in the planning process. My personal opinion is that NASA Aeronautics funding must have a larger external component to effectively engage with universities and industry.

Q3. External Research: How much research should be contracted out to industry and academia?

A3. As stated in the report:

> "As of January 2006, NASA seemed intent on allocating 93 percent of NASA's aeronautics research funding for in-house use. While the committee has no specific recommendation on the in-house/external split, it does not believe that such a split would serve the best interests of NASA or the Nation."

The committee did not feel justified in naming a particular percentage split, but it did conclude that a split of 93/7 would not adequately involve industry and academia. Also, the split should be such that it ensures that NASA can adequately perform five tasks:

> "(1) identify technologically important problems, the answers to which can benefit the Nation, (2) advance important pre-competitive R&T that would not otherwise be done, (3) leverage industry research funded by other agencies or industry itself, (4) ensure that the results of NASA aeronautics research take into account relevant standards and practices, and (5) facilitate the transfer of research results to industry so that they find valuable, real-world applications."

In addition, in my personal opinion, for purposes of determining whether industry and academia are adequately involved in NASA R&T, the definition of in-house funding should include funding used to pay for support service contractors and other contractors who work on-site at NASA facilities essentially as adjunct NASA employees.

Q4. Organizational Options: Recommendation number eight states: "The U.S. Government should conduct a high-level review of organizational options for ensuring U.S. leadership in civil aeronautics." Can you give us some examples of organizational options that might be considered? Should we consider moving civil aeronautics research out of NASA?

A4. In my personal opinion, aside from the "business-as-usual" approach, the range of organizational options might include consolidating all aeronautics research under another agency, which might be NASA, but might also be an agency such as a National Aeronautics Agency, or a National Aeronatics Institute under DOT or DOC; consolidating under an academic consortia, similar to the way AURA manages many of the world's observatories; or consolidating under a nonprofit, the way an FFRDC is run. Moving civil aeronautics research out of NASA should definitely be considered.

Q5. NASA Research Facilities: If NASA's aeronautics budget remains unchanged, should NASA consider closing some of their research facilities, and dismissing affiliated scientists and engineers, in order to bolster available research funding? How should NASA balance keeping key facilities and workforce in place, with doing actual research?

A5. While the Decadal Survey committee was, in general, in favor of testing facilities, and felt that it was important for NASA to "seek a business model that will generate the optimal combination of income and utilization," it deferred to a number of other recent studies which are completely devoted to this topic, including:

Anton, P.S., E.C. Gritton, R. Mesic, and P. Steinberg. 2004. *Wind Tunnel and Propulsion Test Facilities: An Assessment of NASA's Capabilities to Serve National Needs.* Santa Monica, Calif: RAND Corporation. Available online at: *ntrs.nasa.gov/index.cgi?method=ordering&oaiID=oai:casi.ntrs.nasa.gov:20050199428*

Kegelman, J. 2006. *Wind Tunnel Enterprise.* NASA Langley Research Center. Available online at: *http://windtunnels.larc.nasa.gov/enterprise.htm*

National Research Council (NRC). 1994. *Aeronautical Facilities: Assessing the National Plan for Aeronautical Ground Test Facilities.* Washington, D.C.: National Academy Press. Available online at: *http://fermat.nap.edu/catalog/9088.html*

NRC. 2004. *Investments in Federal Facilities: Asset Management Strategies for the 21st Century.* Washington, D.C.: The National Academies Press. Available online at: *http://fermat.nap.edu/catalog/11012.html*

My personal opinion is that a strategy that rules out the possibility of reducing staff and facilities in the face of extensive budget cuts, such as those that the NASA aeronautics program has endured over the last decade, is an unrealistic strategy that avoids making hard decisions, but which exacerbates the corrosive effect that budget cuts have on the quantity and quality of NASA aeronautics research, as a greater and greater percentage of the budget is devoted to sustaining aging facilities and an aging workforce that is oversized compared to the available funding. My greatest concern about the current strategy and funding is the lack of "seed corn" (principally people) for the future.

Q6. Civil Research Aircraft: NASA is proposing to dispose of its fleet of civil aviation research aircraft. They include a Boeing 757 and a mix of general aviation aircraft. Given the direction of future aeronautics research, especially with the emphasis on foundational and airspace systems research, do you think it makes sense for NASA to continue owning and operating these aircraft?

A6. As stated in the report,

"It is important to note that (X-planes] are not limited to high TRL research. While an X-plane may represent a system prototype (TRL 7), it may also be used to observe basic phenomena, prove concepts, or validate a component or subsystem (TRL 1–6)."

A similar sentiment could be applied to other research aircraft. In addition, the committee concluded that code validation is an extremely important role NASA can play, which, in some cases, could require flight testing. NASA's budget situation may necessitate these sorts of decisions, but it is my opinion that a focus on fundamental research should not, in and of itself, preclude the necessity or value of research aircraft.

Q7. Demonstration Projects: What are your views about NASA's decision to drop the four demonstration projects (zero emissions aircraft; subsonic noise reduction; high altitude, long endurance, remotely piloted UAV; and sonic boom reduction) proposed in last year's budget? Would their results have been of limited value to industry and government? Were their objectives too narrow in scope? In the current budget, would they have squeezed out too much basic research?

A7. The report did not offer any comment on these specific projects. In my opinion, at least two of these demonstrations should have been funded.. . .

Q8. Technology Maturity Level: How should NASA decide what technologies to pursue to a higher maturity level, and to what level they should be taken?

A8. From the report:

"NASA has historically supported research through TRL 6 and then transferred research results to industry, with the expectation that industry would continue development of new technologies through TRL 9. The [Decadal Survey] steering committee, however, believes that different transfer points are often appropriate, because industry's interest in developing new technologies varies based on urgency and expected payoff. For urgent, high payoff applications, for example, it may be sufficient for NASA to mature technologies to TRL 5.

When NASA is developing technologies for transfer to operational federal agencies such as the FAA, the committee believes that research results should normally be transferred to industry first, to ensure product support, enhancement, integration with other systems, and certification. For government agencies that include an R&D mission, agency-to-agency transfer is appropriate, and such transfers may occur at reasonably low TRLs (e.g., TRL 3)."

Questions submitted by Representative Mark Udall

Q1. In your opinion, who should NASA's aeronautics program be serving? What specific measures can Congress use to determine whether NASA has a successful and relevant aeronautics research program?

A1. The Decadal Survey focused on civil aeronautics research.Absent a national aeronautics policy, the Committee concluded that the civil portion of NASA's aeronautics portfolio should primarily serve the air transportation system, where

"The air transportation system includes passenger and cargo airlines; general aviation, including business aviation; and the national airspace system, including airports, ATM facilities, and operational elements of the Federal Aviation

Administration (FAA). U.S. civil aviation includes all of the above, plus manufacturers and research organizations in government, industry, and academia."

The Committee felt that the most important outcomes of a successful and relevant aeronautics research program were capacity, "the maximum amount of people and goods that can be moved through the air transportation system per unit time regardless of environmental conditions," and safety and reliability, "the ability of the air transportation system to meet expectations with regard to reductions in fatalities, injuries, loss of goods, and equipment damage or malfunction." Secondary outcomes were improved efficiency and performance that would "increase substantially air transportation system capacity per unit resource," and benefits to energy and the environment that "minimiz[e] the negative impact of the air transportation on the Earth, its atmosphere, and its natural resources." In addition, a successful and relevant program may have important synergies with the space program, and with national and homeland security. However, these benefits should only come as a side effect of other research that already satisfies some or all of the top four objectives.

In other words, research and areas such as hypersonics are important to the space program and some military applications. However, in my opinion, the current approach to organizing and funding NASA aeronautics research, which includes research applicable to civil aeronautics and the space program, makes the aeronautics program at least in part, an adjunct to the space program, and it disguises the extent to which NASA's traditional aeronautics program has been defunded in the last decade by including funding for some space-related research within the aeronautics program.

Q2. Among potential R&D funding areas within the NASA aeronautics budget, what level of priority would you assign to supporting the plan of the JPDO for developing the next generation air transportation system?

A2. The committee felt that the two most important objectives of civil aeronautics research were capacity and safety, which are also goals of the NGATS As a result, many of the high priority R&T Challenges would have great relevance to the JPDO, especially in Areas D and E. However, many of these technologies are long-term research that might not come to fruition for decades. The committee did not specifically address the body of research that is considered to be in support of the JPDO. However, my personal opinion is that in addition to the technologies in Areas D and E, research related to the two identified "barriers " is key to the JPDO.

Q3. A long-standing issue associated with NASA's aeronautics program is how to ensure that research done at NASA actually gets transitioned to industry and other users. Given that you have testified that NASA needs to be prepared to take research and technology initiatives to a higher level of technology maturity than would occur if NASA were just to focus on basic research:

Q3a. How should that be done-for example, through flight test demonstrations or prototype development?

A3a. The report states:

"NASA should embrace a comprehensive roadmap of foundational research that develops discipline-specific and multi-disciplinary capabilities, including system-level design. The roadmap should include (1) progressive empirical validation up to and including a limited number of flight demonstration vehicles (X-planes), (2) technology readiness metrics, such as NASA's technology readiness levels (TRLs). . ., and (3) research partnerships with industry, academia, and other federal agencies. X-planes have played and will continue to play a crucial role in the advancement of aeronautical research by validating the practicality and robustness of specific technological advances. It is important to note that they are not limited to high TRL research. While an X-plane may represent a system prototype (TRL 7), it may also be used to observe basic phenomena, prove concepts, or validate a component or subsystem (TRL 1–6)."

This approach would require NASA to allocate a larger percentage of its aeronautics research budget to external organizations.

Q3b. What fraction of the overall NASA aeronautics budget do you think should be devoted to such technology maturation efforts?

A3b. Please see the answer to Question 3 from Chairman Calvert.

Q4. Do you think that NASA's restructured aeronautics program is consistent with the recommendations of your two National Academies committees, and if not, what problems need to be addressed?

A4. NASA's aeronautics program has not yet been released in detail. As stated in the report, based on information currently available, there is concern that industry and academia have not been sufficiently included in the new program.

Q5. Did NASA ask your committee to brief them on your study? Did you offer?

A5. It is the policy of the NRC to brief the sponsor of a report. The Decadal Survey was briefed to Lisa Porter and her staff on May 31, 2006, about five days before the report was released to the public.

Q5a. If so, what was NASA's reaction? Did they indicate whether or not they agree with your findings and recommendations?

A5a. NASA seemed generally pleased with the report, although Dr. Porter stated at the time that she had not had time to read the entire document (embargoed copies of the report had been provided to NASA on May 25). She indicated that she would have preferred that the report cover all of federal aeronautics research, rather than just civil (but that was beyond the contractual scope of the study). She also indicated approval of the QFD process, given its adaptability to changing goals and priorities. She asserted that the 93/7 split between in-house/external funding (which is quoted in the report) under-reports the amount of funding going to external organizations, but her office has not provided any data to substantiate any other level, despite repeated requests from the committee before the report went to publication.

Q5b. Did they make any commitment to implement your committee's recommendations?

A5b. No.

Q5c. Have they asked for any follow-up with your committee to discuss any of the topics addressed in your report?

A5c. No.

Q6. Your testimony highlighted a little-noted connection between aeronautics research and certification standards for aircraft and aviation equipment.

Q6a. Would you please elaborate on why you think it is important for NASA to conduct research related to certification requirements. How should NASA go about carrying out such research?

A6a. Please see the answer to Question 1 from Chairman Calvert.

Q6b. Do you have any specific examples of how research has improved certification programs and tools?

A6b. The implementation of (1) automated flight control systems that use complex software and fly-by-wire technology in place of manually controlled systems with hydraulic actuators and (2) composite structural materials to replace metal structures has required extensive research to demonstrate required levels of safety, reliability, and fault tolerance. In both of these examples, the new technologies were so different from the technologies they replaced that certification approaches used for the old technologies generally did not apply to the new technologies, because the new technologies were not subject to many of the failure modes associated with the old technologies, but were susceptible to new failure modes to which old technologies were immune and, thus, were not addressed by old certification standards.

Q7. To what level of maturity should NASA be prepared to take technologies in its role of supporting the Joint Planning and Development Office (JPDO) that is developing the next generation air transportation system?

A7. Not all technologies that support the JPDO need to be taken to the same readiness level. As with all technologies, the decision should be made based on the nature of the transition. Different transfer points are often appropriate, because industry's interest in developing new technologies varies based on urgency and expected payoff. For urgent, high payoff applications, for example, it may be sufficient for NASA to mature technologies to TRL 5.

When NASA is developing technologies for transfer to operational federal agencies such as the FAA, the committee believes that research results should normally be transferred to industry first, to ensure product support, enhancement, integration with other systems, and certification. For government agencies that include an R&D mission, agency-to-agency transfer is appropriate, and such transfers may occur at reasonably low TRLs (e.g., TRL 3).

Nonetheless, in my opinion, an aeronautics research strategy that anticipates that industry will *routinely* adopt new technology without NASA maturing that technology to a TRL of at least 6 is unlikely to succeed.

Q8. Your committee's prioritized set of R&D challenges includes several in the area of hypersonics research, although the hypersonics research challenges identified have relatively low rankings on you overall list of priorities. However, under NASA's restructured aeronautics R&D plan, fully 25 percent ($114 million) of the $447.2 million allocated for NASA's Fundamental Aeronautics Program in Fiscal Year 2007 would be dedicated to hypersonics, with NASA arguing for its need "because all access to Earth or planetary orbit, and all entry from orbit through an atmosphere, requires hypersonic flight." Based on the findings of your committee, is that an appropriate prioritization within the constrained resources available to the NASA aeronautics program? If not, what would you recommend be done?

A8. The Decadal Survey Committee felt that research in all speed regimes was beneficial, and as mentioned, several R&T Challenges relating to hypersonics appeared in the list of Top R&T Challenges, especially those that related to multiple speed regimes. That being said, the Decadal Survey was mandated to only consider civil aeronautics. Since hypersonics was judged to have a limited role in the air transportation system, hypersonic-related challenges tended to score poorly. The committee felt that if NASA aeronautics is to pursue a technology whose primary value is to someone else (such as NASA's space program), then that program should provide the funding. The current arrangement uses the aeronautics program to subsidize the space program. In my opinion, because space, civil aeronautics, and national and homeland security are such different missions, it would be more appropriate for NASA to decide, at an agency level, how much funding it will allocate to the space program (research and operations), how much it will allocate to civil aeronautics, (and how much it will allocate to national and homeland security). Priorities and goals within each of those areas could then be used to allocate funding within each area.

Q9. One of the concerns expressed in your committee's report is that under NASA's restructured aeronautics program, the bulk of the aeronautics funding is for "in-house" research at NASA Centers. Your committee believes that there needs to be a more balanced allocation, with more R&D being done with universities, industry, and other organizations.

Q9a. Do you have an estimate of what fraction of the aeronautics research program should be carried out "in-house" at NASA and what fraction should be done elsewhere?

A9a. The committee did not feel justified in naming a particular percentage split (see *the answer to Question 3 by Chairman Calvert*). My personal opinion is that the roughly 50–50 split representative of past aeronautics funding is a more appropriate balance.

Q9b. How should NASA go about determining what research to keep "in-house" and what research to have done elsewhere?

A9b. From the report:

"NASA's aeronautics program is likely to operate in an environment of constrained resources for the foreseeable future. Nonetheless, the committee believes that NASA must meet its commitment to the Nation as the leader of cutting-edge aeronautics research. This requires NASA to carry out, at a minimum, the following missions:

1. Perform cutting-edge, high-value aeronautics research in support of the Nation's future industrial and government aeronautics needs.

2. Maintain in-house technical expertise to advise other parts of the. U.S. Government, including the FAA, the Environmental Protection Agency, and DOD, on relevant aeronautics issues.

3. Maintain state-of-the-art research, testing, computational, and analytical capabilities in support of the U.S. civil aviation community, including industry, academia, and the general public.

4. Facilitate the exchange of information on civil aeronautics R&T among academia, industry, U.S. Government agencies, and the international regulatory community.

5. Provide aeronautics expertise and capabilities in support of NASA's space program.

For NASA to complete these missions in a constrained fiscal environment, the committee believes that NASA must consider the criteria listed below when considering whether to perform the work in-house by NASA engineers and technical specialists or externally by industry and/or universities:

- Specialized technical expertise of in-house and external organizations.
- Specialized facilities and capabilities, such as wind tunnels, simulators, laboratories, and analytical methods, that are available in-house and at external organizations.
- The requirement for NASA to have the expertise and experience necessary to be an informed buyer of aeronautics R&T.
- The requirement for NASA to provide independent technical advice to other federal agencies on aeronautics issues."

Questions submitted by Representative Michael M. Honda

Q1. NASA has been restructuring its aviation safety program. In addition to reducing the aviation safety budget, it has been reducing support for aviation safety human factors research. One consequence has been the loss of aviation safety human factors researchers and expertise from both NASA and the universities.

Q1a. How concerned should we be about the cuts to NASA's aviation safety human factors research program?

A1a. This question was beyond the scope of the Decadal Survey, but in my personal opinion, safety human factors research is an important element of the Certification and Change Management Barriers that we identified.

Q1b. What priority did your committee assign to human factors research?

A1b. A number of R&T Challenges related to human factors were considered by Panels D and E.

From Panel D, "distributed decision-making, decision-making under uncertainty, and flight path planning and prediction was rated 2nd, a "human-machine integration" ranked 8th, and "synthetic and enhanced vision systems" ranked 9th, out of fourteen R&T Challenges.

From Panel E, "appropriate roles of humans and automated systems for separation assurance, including the feasibility and merits of highly automated separation assurance systems," ranked 3rd, "interfaces that ensure effective information sharing and coordination among ground-based and airborne human and machine agents," ranked 5th, and "transparent and collaborative decision support systems" and "interfaces and procedures that support human operators in effective task and attention management," were two of the Challenges in a three-way tie for 8th, out of twenty R&T Challenges.

ANSWERS TO POST-HEARING QUESTIONS

Responses by Stephen A. Merrill, Study Director, National Research Council's "Aeronautics Innovation: NASA's Challenges and Opportunities"

Questions submitted by Chairman Ken Calvert

Q1. External Community: From your perspective, has NASA done a good job of reaching out to its stakeholders, customers, and partners in developing its plans? What do you recommend NASA do to improve those relationships?

A1. As I mentioned in my testimony the Academies' Committee on Innovation Models for Aeronautics Technologies observed the first attempt by ARMD to refocus the vehicle systems program on four technologies with breakthrough potential. We approved the effort to adjust NASA's aeronautics mission to available resources although we did not pass judgment on the project selection. We observed, however, that the program was revised without any serious consultation with its customers—in part because it took place in the context of closed door budget negotiations between NASA and OMB. As a result the program revision had little support and was stillborn. That is an important lesson for future program changes.

Our report, *Aeronautics Innovation: NASA's Challenges and Opportunities,* underscores the importance of close consultation between the agency and prospective users of NASA-developed technologies at every stage of the R&D process from conceptualization and planning to execution. It makes several specific recommendations in this regard, including involvement of stakeholders in so-called decision gate processes and identification of Technology Readiness Level objectives, rotation and secondment of personnel, involvement of stakeholders in events to showcase NASA employee ideas, and extension of the Centennial Challenge prizes to aeronautics.

Q2. External Research: How much research should be contracted out to industry and academia?

A2. Unlike the Academies' Decadal Survey panel, the Innovation Models committee did not address the question of what proportion of the R&D work should contracted out vs. done in house.

Q3. NASA Research Facilities: If NASA's aeronautics budget remains unchanged, should NASA consider closing some of their research facilities, and dismissing affiliated scientists and engineers, in order to bolster available research funding? How should NASA balance keeping key facilities and workforce in place, with doing actual research? How much of a workforce do they need?

A3. Aeronautics Innovation points out that maintaining a legacy infrastructure of centers, research facilities, and employees imposes a severe constraint on flexibility in allocating resources to R&D projects. It recognizes that a more focused mission reflecting current budget realities probably entails some reduction of capacity but does not address ARMD's program in sufficient detail to recommend staffing levels or changes in facilities.

Q4. Technology Maturity Level: How should NASA decide what technologies to pursue to a higher maturity level, and to what level they should be taken?

A4. The *Aeronautics Innovation* report argues for flexibility in determining project TR levels on the basis of a) the technical capabilities of the respective parties (NASA and the intended technology users) and b) the risk profile of the intended users. These can only be assessed in the consultative process described above.

Questions submitted by Representative Mark Udall

Q1. In your opinion, who should NASA's aeronautics program be serving? What specific measures can Congress use to determine whether NASA has a successful and relevant aeronautics research program?

A1. NASA's aeronautics program should be serving the public interest in an efficient, safe, environmentally benign air transportation system by conducting R&D that serves these public goods and in which private interests have limited incentives to invest. Which programs and projects meet these tests are matters of judgment. The success of NASA's efforts should be measured by the degree to which the technologies developed by NASA are implemented and meet their objectives.

Q2. Among potential R&D funding areas within the NASA aeronautics budget, what level of priority would you assign to supporting the plan of the JPDO for developing the next generation air transportation system?

A2. The Academies' Committee on Innovation Models for Aeronautics Technologies concluded that NASA's contributions to a modernized air traffic management system capable of handling increased capacity should have very high priority. The JPDO is Congress' chosen instrument for developing and implementing such a system and the committee, while not evaluating its progress to date in detail, concluded that it is a promising concept.

Q3. A long-standing issue associated with NASA's aeronautics program is how to ensure that research done at NASA actually gets transitioned to industry and other users. Given that you have testified that NASA needs to be prepared to take research and technology initiatives to a higher level of technology maturity than would occur if NASA were just to focus on basic research:

- *How should that be done—for example, through flight test demonstrations or prototype development?*
- *What fraction of the overall NASA aeronautics budget do you think should be devoted to such technology maturation efforts?*

A3. Both the character of higher TR Level projects (e.g., whether flight tests or prototypes) and their share of the aeronautics budget show flow from a careful prioritization of programs and projects. We do not believe they can be specified a priori.

Q4. Do you think that NASA's restructured aeronautics program is consistent with the recommendations of your two National Academies committees, and if not, what problems need to be addressed?

A4. The Academies' Committee on Innovation Models for Aeronautics Technologies did not review the most recent (and ongoing) restructuring of the ARMD program but did consider whether a retrenchment to support of basic or fundamental research is the best course given the declining aeronautics budget. The committee concluded that support of fundamental research is important but not sufficient to accomplish the Federal Government's legitimate role in advancing the air transportation system. There will remain a "valley of death" between fundamental research results and systems innovation. Moreover, the support of technology users needed to sustain NASA's role in aeronautics will very likely continue to wane, undermining even its contributions to research.

Q5. Did NASA ask your committee to brief them on your study? Did you offer?

- *If so, what was NASA's reaction? Did they indicate whether or not they agree with your findings and recommendations?*
- *Did they make any commitment to implement your committee's recommendations?*
- *Have they asked for any follow-up with your committee to discuss any of the topics addressed in your report?*

A5. The committee repeatedly offered to brief NASA officials on its report, *Aeronautics Innovation: NASA's Challenges and Opportunities,* but to date has not been offered such an opportunity.

ANSWERS TO POST-HEARING QUESTIONS

Responses by Michael Romanowski, Vice President for Civil Aviation, Aerospace Industries Association

Questions submitted by Chairman Ken Calvert

Q1. External Community: From your perspective, has NASA done a good job of reaching out to its stakeholders, customers, and partners in developing its plans? What do you recommend NASA do to improve those relationships?

A1. NASA announced its plan to internalize and narrow the focus of its planned research in January 2006. This unilateral redirection to internalize its programs and focus exclusively on fundamental aeronautics research was without input from industry as to the types of research to be accomplished, and the degree to which that research will be carried out. Coupled with this change are significant cuts to the NASA aeronautics budget in the amount of $187.9 million. We are extremely concerned that both this redirection and these significant cuts are being made to NASA's aeronautics program before the national aeronautics policy is written and its research roadmaps are delivered. Rather than the limited engagement we have had, we would like to have an open engagement with NASA as a stakeholder in the development of the national aeronautics policy. The country would benefit from industry having cooperative engagement with NASA throughout the planning as well as through the program execution. We would like to work with NASA to develop appropriate vehicles for collaborative development of NASA's aeronautics work program.

NASA should reach out to industry and other stakeholders to establish both formal and informal means for them to work with NASA in defining and executing a robust aeronautics research and development (R&D) program that has lasting benefits to our nation.

Q2. External Research: How much research should be contracted out to industry and academia?

A2. We understand that NASA has historically contracted out fifty percent of its aeronautics research. Restoring this level would represent an excellent long-range goal. In the meantime, simply maintaining fiscal year (FY) 2007 aeronautics funding at the FY 2006 enacted amount of $912.3 million would provide a twenty percent increase ($188 million) over the Administration's request. This should be used exclusively towards needed transitional research (e.g., demonstrations) and also be open for competitive bids and contracting. This would be a good starting point—especially in view of the current significant shortfall that we know exists for critical next generation air transportation systems (NGATS) research. As we move forward and build a more healthy NASA aeronautics policy, this percentage should grow.

Q3. NASA Research Facilities: If NASA's aeronautics budget remains unchanged, should NASA consider closing some of their research facilities, and dismissing affiliated scientists and engineers, in order to bolster available research funding? How should NASA balance keeping key facilities and workforce in place, with doing actual research? How much of a workforce do they need?

A3. Though NASA should consider doing an assessment of its facilities and workforce similar to industry's practice to ensure sufficiency, NASA also needs to remember its historic role to promote continued United States leadership of aeronautics research and to pragmatically address issues of leadership, vision, relevance, and transition from research to development. Because of the cyclical nature of the industry, NASA must manage its human capital accordingly.

If implemented and appropriately maintained, NASA's 2005 Aeronautics Test Program (ATP) should create stable, sufficient funding and help enhance the strategic and business management of the aeronautics wind tunnels/ground test facilities at Ames, Glenn, Langley Research Centers, and the Dryden Flight Research Center. Funding for these critical NASA facility capabilities, and those that are transferred to DOD or to other agency ownership and operation, must continue to be maintained. It is imperative that cost-effective, state-of-the-art national test facilities are available for both industry and government to meet future civil and defense aeronautics research needs.

Q4. Technology Maturity Level: How should NASA decide what technologies to pursue to a higher maturity level, and to what level they should be taken?

A4. NASA should work in partnership with industry stakeholders and other government agencies to decide which technologies to pursue based on criteria such as national objectives, public benefit, and market potential. For discussion we can divide the range of research into three segments to describe its technological maturity level and be used to illustrate the appropriate roles for government and industry: fundamental, transitional, and applied research. Government has a leading role in fundamental and transitional research due to the inherent risks and the lack of a clear business case application associated with technologies at this level of maturity. Properly conducted transitional research will take the concepts and technologies to a point where their viability for near-term or longer term applications can clearly be determined. Where applicable, it will also enable development of standards for incorporation of advanced technologies into products, whether for use in the domestic civil aviation infrastructure or for placement in the competitive global marketplace. Industry has the leading role at the applied research maturity level, where a significant investment is required to incorporate validated, advanced technologies and concepts into the next generation products for the marketplace.

Fundamental research in advanced fixed and rotary wing aircraft and propulsion and systems technologies, spanning the subsonic, supersonic and hypersonic fields, is important. From this fundamental research a bridge to transitional research is needed to validate which high-risk fundamental technologies are truly applicable and feasible for application into products. It is critical for NASA to define and conduct this transitional research in partnership with industry and other relevant government-agency stakeholders to ensure that the technologies and concepts being explored are aligned with the needs of the public, whether those needs are reflected in the needs for government infrastructure or marketplace needs.

Questions submitted by Representative Mark Udall

Q1. In your opinion, who should NASA's aeronautics program be serving? What specific measures can Congress use to determine whether NASA has a successful and relevant aeronautics research program?

A1. NASA's ultimate customers are the American people and it has the responsibility to ensure that its research program provides tangible public benefits. To best serve the American public, NASA must create a robust aeronautics plan that includes innovative ideas and embraces original ways of implementing those ideas. However, NASA must recognize that, with a few exceptions, the general public does not implement the results or products from the research program. Instead, both government and the general public rely on industry to incorporate the results of NASA's research into new systems and products that improve our nation's infrastructure and quality of life. Therefore, it is imperative that NASA's aeronautics research program includes a robust transitional research component that lays a solid foundation for industry to explore inventive ways to apply that research and perform the follow-on applied research and development necessary for market and public applications.

NASA should serve the needs of the full air transportation system. It should focus on developing and transitioning to industry and government implementers as many high-impact concepts and technologies for moving aircraft, passengers, and cargo in the fastest, safest, and most reliable, affordable, convenient and environmentally friendly manner possible. A relevant and robust NASA aeronautics program will foster the development and implementation of the advanced vehicles (airplanes, rotorcraft, and unmanned aerial systems across a range of applications) and associated systems (propulsion, avionics, air traffic management) that will meet these objectives and ensure the long-term vitality and competitiveness of the U.S. economy.

There are many possible metrics Congress may use to determine whether NASA's aeronautics research is relevant to industry and, by extension, to the American people. Any metrics used should be constructed to not only promote enhanced stakeholder engagement, but also to promote innovation and risk-taking. We believe the following set of metrics will provide the desired transparency for Congressional oversight and also promote a relevant aeronautics program.

The first metric we propose is grounded on the premise that, regardless of the funding source, industry has little desire to engage in any research that is not relevant to their critical R&D needs and overall product development strategies. Given this premise, we propose that the actual percentage of the NASA aeronautics budget that is allocated to cooperative programs with industry offers an excellent metric. Because of precedent, we recommend that at least fifty percent of the budget be used to partner with industry to conduct high-risk transitional research, such as experiments that demonstrate or investigate groundbreaking aeronautical vehicle concepts and other advanced systems. We note that NASA's past investments have led to a broad range of aeronautical breakthroughs ranging from tilt-rotor aircraft, high-altitude surveillance aircraft to the aero-elastic tailoring methodologies that were demonstrated in the X–29 aircraft.

The second metric we recommend is that of the U.S. market share in areas of NASA aeronautics investment. This metric is indicative of how successfully NASA's research investments reach their ultimate customers—the U.S. people and traveling public. We strongly recommend that this metric be underpinned by metrics that highlight measurement of US leadership in the key technology areas identified in a government-industry developed aeronautics roadmap. Those key technology areas identified in the Decadal Study and last year's National Institute of Aerospace (NIA) report form an excellent basis for comparison. To implement this recommendation, we request that Congress sponsor an independent study to benchmark the status of NASA's research leadership in each key technology area. Congress should then monitor NASA's progress towards either attaining or retaining U.S. leadership in each area.

Q2. Among potential R&D funding areas within the NASA aeronautics budget, what level of priority would you assign to supporting the plan of the JPDO for developing the next generation air transportation system?

A2. Supporting the R&D needs of NGATS/JPDO with both fundamental and transitional research must be one of NASA's top aeronautic budgetary priorities.

Q3. A long-standing issue associated with NASA's aeronautics program is how to ensure that research done at NASA actually gets transitioned to industry and other users. Given that you have testified that NASA needs to be prepared to take research and technology initiatives to a higher level of technology maturity than would occur if NASA were just to focus on basic research:

Q3a. How should that be done—for example, through flight test demonstrations or prototype development?

A3a. We agree with the Decadal study that the comprehensive roadmap of foundational research should include: (1) progressive empirical validation up to and including a limited number of flight demonstration vehicles (X-planes); (2) technology readiness metrics, such as NASA's technology readiness levels (TRLs); and (3) research partnerships with industry, academia and other federal agencies.

Any type of transitional research method that takes fundamental research to a higher level is appropriate. This includes both flight test demonstrations and prototype development. NASA and industry should work together to define suitable transitional research programs that have broad applicability and serve national objectives. We are concerned that fundamental research conducted by NASA could be wasted if subsequent transitional research is neither suitable nor performed. Transitional research does not imply that an article is ready to be put "on the shelf for consumers." While an X-plane may represent a system prototype (TRL 7), it is often necessary to examine questions that cannot be answered by existing computers or laboratory methods. The demonstrator can provide a wealth of data that can be used for years to come: enabling observation of fundamental phenomena, proving or refuting broad concepts, or investigating the principles, performance or interactions of novel components, subsystems, or validating new computational or advanced laboratory experimental methodologies (TRL 1–6). An example of how long this process can take is the XV–15. Over twenty years ago, NASA stopped doing research on the XV–15 after bringing the research to a transitional level (TRL 6); since then, industry has been working to use this technology to create military and civilian aircraft (TRL 7–10).

Q3b. What fraction of the overall NASA aeronautics budget do you think should be devoted to such technology maturation efforts?

A3b. If we take "technology maturation efforts" to mean transitional research, then it is appropriate that these efforts grow to approximately 50 percent of the budget over the long-term, which we believe is consistent with historical practice at NASA. As I stated in my testimony, NASA is eliminating transitional research from its aeronautics program while it is requesting 20 percent less funding. Instead of reducing aeronautics funding by $188 million for FY 2007, Congress should maintain funding at the FY 2006 enacted level of $912.3 million and require that NASA immediately apply this increased portion of the FY 2007 funds to transitional research programs that are defined and performed in partnership with NASA's industry and government stakeholders.

Q4. Your testimony highlighted a little-noted connection between aeronautics research and certification standards for aircraft and aviation equipment.

Q4a. Would you please elaborate on why you think it is important for NASA to conduct research related to certification requirements. How should NASA go about carrying out such research?

A4a. NASA has a role in two areas related to the certification of aviation products for use in private-sector or governmental infrastructure. The first relates to NASA's ability to advance the state-of-the-art in analytical, computational and experimental methods and tools. NASA has made lasting contributions in a wide range of applications including structural analysis, structural dynamics, impact analysis, aerodynamics, computational fluid dynamics, and others. Adoption and recognition of these advancements by both industry and the FAA leads to improved certification by enhanced understanding of a product's behavior under a wide-variety of conditions. These new capabilities also speed up time-to-market for new products and reduce development costs, thereby enhancing U.S. industry's competitiveness. The second area where NASA can make strong contribution is conducting research that supports rule-making and specifications for government-regulated systems. NASA is in a unique position to work with both industry and other government agencies to conduct broadly accepted transitional research that can provide a wealth of data to support rule-making. NASA research can also prove fundamental concepts and their capabilities to allow specifications to be developed for governmental infrastructure such as advanced air traffic control capabilities.

An example where NASA research should play a leading role in the development of enabling regulations relates to supersonic aircraft flight over land. Current FAA regulations prohibit supersonic flight over land due to the disruptive environmental effects of sonic booms. However, recent NASA-industry research shows that it is possible to modify aircraft shapes to virtually eliminate the sonic boom, which could open the door for a new flight regime in our air transportation system. However, before this can be achieved, the regulations must be changed. A significant research program is required to collect a sufficient amount of data to enable the FAA to change the regulations to a performance-based standard. We believe that conducting this research is an appropriate governmental role that will have lasting public benefits. Governmental leadership of the research program will also ensure that the data supporting such a regulatory change would be widely accepted during the public rule-making process.

In developing the Next Generation Air Transportation System (NGATS), a significant amount of work is needed to build on the fundamental aeronautics research that NASA is conducting on air traffic management technologies and to validate their suitability for today's and tomorrow's systems. Work must be done in an operational or realistic near-operational environment to allow the government to define appropriate specifications for these new systems. Industry cannot design systems for implementation by the government without ensuring that they are designing according to the appropriate specifications. Unfortunately, the FAA currently is not able to conduct this important transitional research by itself. Realistically, the FAA can only do this work in partnership with NASA due to NASA's technical capabilities. However, NASA has not committed its support of this important transitional research.

Q4b. Do you have any specific examples of how research has improved certification programs and tools?

A4b. Decades of joint aeronautics research by NASA and industry have dramatically improved the safety, efficiency, and environmental integrity of air travel. Application of productive research in design and analytical tools that validate a product's design performance characteristics has dramatically improved and accelerated the FAA certification process in numerous areas, while increasing the understanding of the product's behavior under a range of conditions. For example, the implementation of composite structural materials to replace metal structures has required extensive research to demonstrate required levels of safety, reliability, and fault tolerance. The results of this research had to be incorporated into revised certification practices both within the industry and the FAA to ensure that the different characteristics are appropriately validated in new products.

Q5. NASA apparently developed its research priorities for its restructured aeronautics program internally rather than asking the National Academies or industry to work with them collaboratively to develop those research priorities.

Q5a. Is that correct? What role did industry have in developing the NASA aeronautics research program that was presented at the Reno aerospace sciences conference earlier this year?

A5a. Yes, we believe NASA restructured its aeronautics program internally, rather than working with industry to collaboratively identify research priorities. To our knowledge, industry had no role in development of the "re-directed" NASA aeronautics research program presented at the Reno AIAA Aerospace Sciences Conference in January 2006.

Q5b. What role has industry had since that time?

A5b. Industry's role has been very limited. The new NASA aeronautics R&D program allowed only seven percent of the aeronautics R&D budget to be expended on external research contracts. These contract opportunities are targeted to universities and small firms. While industry can not be legally excluded from applying for these contracts, it is not being encouraged to pursue them. Instead, the process for industry to engage in research with NASA is different. In order to be considered, companies submitted a "request for information" (RFI) on a given area of fundamental research that they wanted to conduct with NASA. Industry participation requires industry cost-sharing or in-kind resources to partner with NASA. Some of the companies that responded to the RFIs have been invited to meetings at NASA regarding the research area that they expressed interest in, but we are told that some still have not heard from NASA regarding their RFI submissions.

Q5c. What role would industry like to have?

A5c. Industry would like to be an integral partner with NASA across the range of aeronautics research planning and execution. NASA should look to external stakeholders for development and execution of its aeronautics programs whenever possible. It is critical that all stakeholders have an opportunity to influence the formation and implementation of federal aeronautics research. This participation will ensure that federal research is relevant and benefits the U.S. taxpayer and U.S. global competitiveness. Relevant research that is eventually deployable to products and applications increases the American public's return-on-investment on several levels, such as job creation, increased tax revenue, new services and new technology application spin-offs.

Industry needs to be a partner with NASA in setting priorities for research areas as well as research maturation levels. Industry invests much more funds on R&D than the amount that is considered each year in the NASA aeronautics budget. But there is more at stake than just research dollars. By itself, government does not build products and implement technologies—the American people, represented by industry, do. Industry-government collaboration on research priorities should be the bridge to relevance and NASA should help build that bridge. Industry wants to partner with NASA and share its expertise to help the U.S. maintain aeronautics leadership and our national and economic security.

Q6. Air transportation plays an increasing critical role in stimulating economic growth and expanding the Nation's ability to compete global product and service markets. What previous NASA research demonstrator vehicles have yielded lasting air transportation improvements and what research demonstrators should NASA and industry explore for the future?

A6. This year marks the 50th anniversary of the landmark X–1 project. This project exemplifies the inspiration and vision we need. The X–1 project defined and solidified the post-war cooperative integration of U.S. military needs, industrial capabilities, and research facilities. The whole X-plane history exemplifies what demonstrators can do to promote economic growth, and to inspire creativity and enrollment in the next generation workforce. Demonstration programs have tremendous inspirational value and draw people to aviation careers, especially advanced engineering. Abandoning of these R&D demonstrations will remove the major tool used to validate fundamental research projects and conduct research that goes beyond that performed in laboratories or on computers. Furthermore, this shift in emphasis will remove one of our nation's most enduring and appealing programs. Highly advanced research aircraft are a hallmark of NASA leadership. Without programs likes these, it is probable that NASA's image as a world leader will suffer significant damage along with its research capability. NASA should continue to pursue appropriate demonstrator vehicles for advanced fixed and rotary wing aircraft, propulsion, and systems, spanning the subsonic, supersonic and hypersonic fields.

Q7. NASA appears to be limiting potential industry-NASA cooperation on any research beyond basic research to "no-exchange-of-funds" Space Act agreements.

Q7a. Is that correct?

A7a. Yes, we understand that NASA has limited only potential industry-NASA cooperative research to "no-exchange-of-funds" Space Act agreements. Although industry cannot be legally excluded from awards on fundamental research, we understand that the seven percent budget target will be contracted outside NASA to universities and small firms.

Q7b. Will such agreements be sufficient to ensure adequate interaction between NASA's research activities and industry's needs?

A7b. No, without more interaction NASA has the potential to create research projects which may never result in a public benefit.

Q7c. What forms of industry-NASA collaboration would you recommend be undertaken?

A7c. We believe NASA should reach out pro-actively to its industry, government, and academic stakeholders to promote collaborative development and execution of its aeronautics research program. It should move forward with a spirit of openness, using both formal and informal means at all organizational levels, and to the maximum degree possible, to create a robust program that enjoys broad ownership and support.

Our first recommendation is to restore a direct advisory committee for the Associate Administrator for Aeronautics. Through this group, NASA could collaborate with industry on creating its research and development priorities and roadmaps.

In addition to industry-NASA collaboration, it is very important (especially in a budget restrictive environment) to have cooperation and integrated R&D planning across the Administration. The Administration's Office of Science and Technology Policy (OSTP) could have a leading role here. OSTP has a National Science and Technology Council that should be coordinating research across the Federal Government. Its Aeronautics Science and Technology (AS&T) Subcommittee is creating the national aeronautics policy. It will also develop the integrated roadmap encompassing all federal aeronautics research. While industry's input into development of policy has been very limited, we believe that industry must have an active and effective role working hand-in-hand with the government members of the AS&T Subcommittee on both developing this roadmap and monitoring its implementation. AIA would enthusiastically work with NASA and OSTP to define and implement an effective framework and method for industry and academic engagement into this process.

The need for integration of aeronautics research planning and execution is especially crucial for JPDO and NGATS research. The JPDO is working across-agencies and with a broad range of stakeholders through the NGATS Institute to develop the overarching needs for NGATS-related (air traffic management, safety, security, etc.) R&D. It is imperative that this research is supported, appropriately funded and executed by the various agency aeronautics research programs. Likewise, the mechanism that is established in conjunction with the AS&T Subcommittee for the full, cross-agency aeronautics roadmap must recognize the existence of the JPDO's efforts. Each agency's advisory committee structure should bring these together into the comprehensive, integrated roadmap backed by the necessary funding, priorities, execution, and accountability.

Q8. In your testimony you state that "industry is willing and prepared to assist the Administration in the development of the national [aeronautics] policy and subsequent research roadmaps." *I assume you have made that offer to NASA and to the White House—what has been their response? Are they involving or planning to involve industry in the development of the policy?*

A8. In October 2005, a representative of the Office of Science and Technology (OSTP), who at that time was the co-chair of the Aerospace Science & Technology (AS&T) Subcommittee tasked with drafting the National Aeronautics Policy, asked AIA to assist in obtaining input on the Policy needs and obtaining feedback on its contents. I recommended that the review be coordinated through the National Center for Advanced Technologies (MCAT), a 501(c)(3) nonprofit organization that is affiliated with AIA since this provided an excellent means for broad participation that would be consistent with the Federal Advisory Committee Act. I am the president of NCAT.

After several more discussions with OSTP in the later part of 2005, I was told that since the draft document was ready for stakeholder review, to expect an imminent transmittal of the draft policy, which we agreed would be distributed for comment to a wide range of stakeholders, including the user-community and research community. However, before the draft document was received I was informed that there had been a change, and that the draft policy document could not be shared, nor could its contents be discussed. Instead, I worked with OSTP in the early part of 2006 to define the need for stakeholder "input sessions," under which representatives from the stakeholder community would be allowed to relay to the AS&T Subcommittee their views on what should be included in the National Aeronautics Policy. However, this would not be an exchange of views; the AS&T Subcommittee would not share its thoughts or direction regarding the policy. Following a March 2006 request for proposals to several organizations to organize the input sessions, NCAT was selected to arrange and host a one-time series of input sessions. These were held, without cost to the government, on April 17, 18, and 20 with the AS&T Subcommittee and representatives of the academic, manufacturer, and user communities respectively. In addition to the verbal input, NCAT forwarded the AS&T Subcommittee written summaries of general input provided at each session as well as any written submissions provided by participants. In each of these meetings, the stakeholders expressed a desire to work more closely with the AS&T subcommittee on the policy and receive feedback as the policy evolved. At a minimum the participants requested additional input sessions. I have pursued the possibility of additional meetings with the AS&T Subcommittee leadership and have been told that there will not be any additional opportunities to provide input on the National Aeronautics Policy or otherwise discuss its contents.

Ouestions submitted by Representative Michael M. Honda

Q1. As part of her restructuring of NASA's aeronautics program, the Associate Administrator is seeking to get rid of NASA's flight research aircraft, most notably the B–757 and six General Aviation aircraft based at the Langley Research Center. In addition, there are reports that NASA's Aeronautics Research Mission Directorate is considering withdrawing its support of the "Future Flight Central" Simulator, the Vertical Motion Simulator, and the Crew Vehicle Systems Research Facility at the NASA Ames Research Center. What would be the impact of such actions on NASA's ability to conduct transitional aeronautics R&D in support of its customers and users?

A1. The negative impact of these facilities being unavailable is hard to quantify, but it will be severe. Some AIA members estimate that it will take one to two years longer, at least, to develop marketable products that serve the public benefit. For example, development of the Synthetic Vision System (SVS), that is expected to be certified next year, was greatly facilitated by use of a test vehicle similar to the 757 (which has also been decommissioned). Decommissioning of these capabilities will seriously impede progress in research relating to new applications. Experimental products such as the SVS were developed to application level because of the collaboration with NASA on research facilities. Moreover, test vehicles such as the 757 are a unique national resource, they are very expensive and hard to replicate. Specifically, there are extremely few large transport technical demonstration research assets available, particularly for avionics and we expect that these capabilities will be instrumental in developing and implementing the Next Generation Air Transportation System.

Q2. NASA's aeronautics test facilities and simulators have been under stress in recent years due to the budgetary squeeze in NASA's aeronautics program.

Q2a. How important are those test facilities and simulators to the Nation, and what would you recommend be done to ensure that needed capabilities are preserved?

A2a. Appropriate test facilities and simulators are vital to maintaining our global competitive advantage and ensuring practical applications that benefit the American public. A secure Aeronautics Test Program (ATP) will protect the strategic availability of the minimum critical suite of wind tunnels and ground test facilities necessary to meet national needs. We applaud NASA for undertaking this initiative. We must also ensure that DOD allocates adequate funding to maintain its test facilities.

Q2b. Does NASA have in place the skilled workforce needed to operate and maintain NASA's aeronautics test facilities and simulators, and do you have any concerns that those personnel could be lost to the agency in the coming years? If so, what should be done?

A2b. Currently NASA appears to have the workforce needed to operate and maintain NASA's aeronautics test facilities and simulators. However, we must recognize the need to guarantee that they have the skilled personnel necessary to fully utilize these critical facilities to their full potential in the coming years. This will be especially challenging if these professionals continue to face an uncertain future that makes pursuing expertise in experimental methods and capabilities an uncertain career path; it will be increasingly difficult to get new candidates to enter the field. Industry is concerned about maintaining cost-effective, state-of-the-art national test facilities to meet future civil and defense aeronautics research needs. We must have a robust national aeronautics plan that takes both the facilities and their operational issues into consideration. It is of vital importance that we improve our experimental methods and train new testing professionals, as well as retain the present workforce.

ANSWERS TO POST-HEARING QUESTIONS

Responses by Parviz Moin, Professor, Mechanical Engineering, Stanford University; Director, Institute for Computational and Mathematical Engineering

Questions submitted by Chairman Ken Calvert

Q1. NASA Research Facilities: If NASA's aeronautics budget remains unchanged, should NASA consider closing some of their research facilities, and dismissing affiliated scientists and engineers in order to bolster available research funding? How should NASA balance keeping key facilities and workforce in place, with doing actual research? How much of a workforce do they need?

A1. Most NASA research facilities, (e.g., large wind tunnels, arch jets) are unique in the U.S. There are comparable facilities in Europe and Russia. Although U.S. aerospace companies have used some foreign facilities, it would not be prudent for the long-term competitiveness of the U.S. civil and military aerospace industry to close and dismantle these unique facilities. A competent operations staff is necessary to maintain these facilities. It is also equally important for NASA to maintain a competent core of research scientists to conduct novel experiments in these facilities, to validate computational models or conduct experiments of discovery in practical realms not possible in small-scale university facilities. I would emphasize that it is important for NASA staff to conduct leading edge research, and not just become a service provider for the utilization of NASA's unique facilities. The research should specifically focus on interdisciplinary aeronautical systems, which would be highly complementary to the standard disciplinary approach pursued by universities. In order to lead and provide coordination for the Nation's aeronautics enterprise NASA must maintain a critical mass of research engineers in all areas of aeronautics. They should be of the highest technical caliber so that they are respected and listened to by both academics and industry. NASA scientists should be evaluated based on standard metrics in the engineering science community such as impact of publications and adaptation of their models and concepts by industry. If the country is to maintain NASA as a research organization, then it must demand that its personnel remain at the forefront of research and not just act as an instrument for dispensing government funds to academia or industry. It is not clear that the current civil service structure for NASA scientists is optimal. However, changing the system requires careful review and assessment of the pros and cons of other models.

Q2. External Research: How much research should be contracted out to industry and academia?

A2. NASA appears to be the only source of academic research funding for civil aeronautics. The funding is used for the creation of new ideas and tools as well as for education of future generations of aerospace engineers. NASA management should determine the extent of the facilities and know- how they require from industry for projects conceived by NASA. These prospective joint projects could involve cost sharing arrangements. NASA should not simply be a conduit for transferring public funds to industry. Industry's natural motivation for excellence in product and thereby increased revenues should drive their pursuit of NASA expertise and intellectual resources, rather than NASA seeking relevance for its research by buying industry's involvement.

Q3. Technology Maturity Level: How should NASA decide what technologies to pursue to a higher maturity level, and to what level they should be taken?

A3. Historically, knowledge has been the most important product of NASA's aeronautics research. NASA should ensure that its advances in knowledge, understanding, tools, methods and technologies transition in a timely manner to the broad U.S. industrial community. The level of maturity of its studies should be commensurate with that required for validation and establishing scientific credibility of its tools, models and design concepts. Industrial leaders should also put a process in place that could evaluate NASA technology for possible transition to industry. NASA programs should be peer reviewed annually by experts from industry and academia.

Questions submitted by Representative Mark Udall

Q1. In your opinion, who should NASA's aeronautics program be serving? What specific measures can congress use to determine whether NASA has a successful and relevant aeronautics research program?

A1. NASA's aeronautics program should serve the tax payers and future generations of Americans by ensuring the preeminence of the United States in civil aeronautics technology and air transportation system, and provide critical support to NASA's space exploration missions. The primary output of NASA has been advancement of knowledge documented in high quality publications, computational tools, experimental methods and data, and aeronautical design concepts. Accordingly, the quality of NASA's output should be evaluated by standard scientific norms and the extent of adaptation of the methods by the broad aeronautical community. Making one sector of the economy, the aerospace industry, the sole customer and evaluator of the quality and relevance of NASA's work has not worked and is contrary to the mission and goals of the agency funded by the tax payers.

Q2. Among potential R&D funding areas within the NASA aeronautics budget, what level of priority would you assign to supporting the plan of the JPDO for developing the next generation air transportation system?

A2. The projected increase in air traffic capacity in the next 10 to 15 years suggests that NASA should assign high priority to conducting research critical to the JPDO vision. The JPDO enterprise should be set up such that NASA's contribution would be what it is equipped to do best, which is to conduct research, including experiments and simulations at its research centers. ARMD's reorganization has recognized air traffic management as one of its core and mission critical components. There is also considerable emphasis for research in this area in the recent NASA Research Announcement (NRA), which solicited basic and applied research proposals from academia and industry.

Q3. In your testimony you state that: "Foundational research is precisely what NASA should be doing; in fact, given the limited resources that the Aeronautics Research Mission Directorate has been given, only foundational research is what it can do successfully." *However, Dr. Merrill testified that his National Academies committee concluded that:* "If [NASA's] Aeronautics Research Mission Directorate is to sustain its relevance and support, it should continue to have a portfolio quite diversified in terms of the stage of technology being developed, even if that means significantly few projects."

Q3a. Why do you feel NASA should confine itself only to basic research at low stages of technology development?

Q3b. How will NASA validate the models you discuss in your testimony or transition your research to a form that is relevant to potential users of the research without undertaking R&D at higher stages of technology development?

A3a,b. As a federal research organization NASA conducts foundational research to advance the knowledge base in the aerospace field. This research is aimed at answering outstanding questions and to gain scientific understandings in broad areas of aeronautics: propulsion, aerodynamics, and air traffic management. In the field of propulsion, for example, outstanding questions remain in the areas of efficiency, safety and emissions of harmful combustion products into the atmosphere. In the area of aerodynamics and air traffic management, NASA is conducting research to understand the mechanics of noise generation and its mitigation near airports. To make supersonic transportation possible for business jets as well as commercial airlines, NASA conducts research aimed at mitigation of the sonic boom. NASA's research output has been in the form of technical reports, computational tools such as the NASTRAN program for structural analysis, experimental data and methods, and design concepts. All of these have been transitioned successfully to the user community and have been used broadly by the aerospace industry. NASA's research should be targeted for the public good (e.g., better and environmentally friendly transportation system) as well as to enhance the economic competitiveness of the Nation's aerospace industry.

Model validation is carried out in a suite of carefully designed experiments. Full scale, or system technology demonstration experiment is only one element of the validation process, which is also very costly. Given the limited available resources, large-scale demonstration projects and prototyping can only be done at the expense of other critical research of public interest. Moreover, the results of such projects often become proprietary assets of select companies who participated in the projects under government contracts, and do not become available to the broad aerospace community. In my opinion, such a preferential treatment is contrary to the mission of NASA as a federal research agency.

Q4. In your testimony you say that "NASA's role in aeronautics research should be as a bridge between academia, which conducts fundamental research, and industry which ultimately ensures the preeminence of the United States in aerospace technology." *When you say NASA's role should be to serve as a "bridge" between academia and industry, it would seem as though you are saying that NASA needs to undertake transitional technology maturation R&D of the kind advocated by Dr. Romanowski and others in industry. Is that what you mean? If not, what specifically* should *NASA do to serve as a "bridge"?*

A4. Academic research is generally small-scale and has disciplinary focus. NASA plays an important leadership role in inspiring and directing academic research to relevant industrial problems. To complement the academic research, NASA's own research should be interdisciplinary and focused on integration of basic research results for aeronautical systems. NASA scientists may also use their unique facilities to validate models conceived in simple configurations, and test design concepts in more relevant configurations of interest to industry. In this regard NASA plays a critical role in facilitating the transition of academic and its own research results to industry.

Appendix 2:

ADDITIONAL MATERIAL FOR THE RECORD

STATEMENT OF DR. ROGER L. SIMPSON
PRESIDENT, AMERICAN INSTITUTE OF AERONAUTICS AND ASTRONAUTICS; HOLDER OF THE COWLING PROFESSORSHIP IN AEROSPACE AND OCEAN ENGINEERING,
VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY
BLACKSBURG, VIRGINIA

Redefining Civil Aeronautics R&D at NASA

The current status of aeronautics research and development in the National Aeronautics and Space Administration (NASA) is clearly at a critical juncture. As a result of today's fiscal constraints, funding for aeronautics research is reaching record lows, with plans for even lower budgets.

As President of the American Institute of Aeronautics and Astronautics, I represent a constituency of over 35,000 aerospace professionals, located in all fifty states and 70 countries internationally. During my tenure as President, I have heard many members at our technical conferences and other venues voice their concerns about the NASA aeronautics research program. These concerns can generally be categorized into three interrelated areas: a crisis in funding which has led to a debate over the strategy for using available funds and to a major impact on the future aeronautics workforce. I will address these concerns in my comments below.

In the invitation letter to provide written testimony for this hearing, I was asked to provide answers to several questions. Below, I respond to these specific questions, and then follow with a more comprehensive discussion that supports and augments my initial answers. I have relied very heavily on my 40 years of experience as an educator and as an active researcher who has produced and continues to produce new aerospace related scientific and engineering information. I have read the recent NASA Aeronautics Research Mission Directorate (ARMD) goals, strategies, and technology themes; the *"Decadal Survey of Civil Aeronautics: Foundation for the Future"* and the *"Aeronautics Innovation: NASA's Challenges and Opportunities,"* both from the National Academies (2006); and the recent NASA Research Opportunities in Aeronautics (ROA–2006) or NRA NNH06ZNH001. I also am familiar with the American Society of Mechanical Engineers (ASME) report, *"Persistent and Critical Issues in the Nation's Aviation and Aeronautics Enterprise,"* November 2003.

QUESTIONS POSED BY THE SUBCOMMITTEE ON SPACE AND AERONAUTICS

1. How would you assess the Aeronautics Research Mission Directorate's program goals and strategies?

Given the proposed ARMD aeronautics budget, the published ARMD program goals and strategies appear appropriate.

Is NASA's emphasis on foundational research appropriate?

Yes. Given the very limited budget, NASA appears to be and should be trying to obtain NEW fundamental information which can be used by other researchers in applied research and development and by industry to develop better lower uncertainty design tools and codes. I understand that ARMD solicited input from industry early in 2006 (NRI) about their most pressing problems before formulating the above mentioned ROA–2006, which was issued on May 23, 2006.

Given the resources currently allocated to it, is ARMD properly structured, and is it pursuing the right lines of research?

In my opinion, yes. As I discuss below, the ARMD and NASA centers have been subjected to many reorganizations and changes in direction over the past 10 years. The time between reorganizations seems to have been shorter than the time required to develop plans, allocate funding, develop personnel and research capabilities, and solve a problem. As a result, a number of areas within aeronautics have not progressed much during recent years. Since ARMD has been very open to academia in the past few months about its program and appears to have interacted with industry to develop a list of the most pressing topics, the NRA topics that were issued on May 23, 2006, appear to be appropriate. Research on all of the topics in my technical area would contribute fundamental new information to advance aeronautics.

2. What should NASA be doing to ensure that its research is relevant to the long-term needs of industry and is used by industry?

It appears that NASA ARMD is on the correct track by involving industry to determine the research problems that can have the greatest impact on improving industrial capabilities. Periodic communications among the researchers, NASA and industry can keep the research activities more focused and increase the opportunities for other research contributions that may not have even been in mind at the outset. Many members of AIAA would argue for an increased openness in dialogue between NASA Headquarters and their industry partners.

What should NASA be doing to help keep the academic research enterprise healthy and to ensure an adequate supply of aeronautics engineers and researchers?

More aeronautics grants should be awarded competitively to graduate degree granting institutions. The academic research enterprise which will produce the next generation of aeronautical engineers is already in distress because of the lack of proper funding. Some aeronautical engineering faculty have left the field because their areas of aeronautics are no longer supported by NASA. Two years ago some grants to universities were abruptly ended with graduate students in the middle of their research, even though the researchers were meeting all goals and requirements.

Graduate fellowships to students alone will not solve the future workforce problem, even though some view this as a less costly way to produce graduate degrees without paying any faculty salaries, lab costs, or indirect costs. Since most of the research ideas come from faculty who dedicate their careers to and are experts in topical areas of research, unless these faculty and their labs are supported, then weak graduates will be produced from out-of-date programs. The faculty will move to research areas where they can obtain stable summer salary support for themselves. Universities cannot afford graduate programs that do not provide sufficient research grant indirect costs and will place resources in other areas than aeronautics.

3. What is your reaction to the conclusions and recommendations of the Decadal Survey?

Given that the proposed budget outlook for ARMD, and that the Decadal Survey did not consider the budget requirements for a properly funded aeronautics research program, then the recommendations and conclusions of the Decadal Survey seem reasonable. Much effort was given to rank order priorities and to ensure that only the most deserving research should be pursued. Many creative and even revolutionary ideas come from the bottom up, so there should be some discretionary funds allocated to each NASA competency area to pursue promising new areas of research.

ASSUMPTIONS ABOUT AERONAUTICS AND THE EFFECT OF THESE ASSUMPTIONS ON NASA AERONAUTICS BUDGETS

It appears clear to me that at some point in the relatively recent past, assumptions were made at high levels in the U.S. Government about the future of aeronautics and aeronautical research in the U.S. While I cannot cite a reference, I have heard comments in the media from time to time that aeronautics is a "technologically mature industry" that does not need further research support or it is "a sunset industry" that will be transitioned offshore and therefore should not be further developed. Both of these ideas are wrong.

Some have posed the questions, "What new aeronautical innovations has NASA produced in recent years? The commercial airplanes look the same as they did 20 years ago. Why should we fund NASA aeronautics at a higher level?" The answers to these questions are that NASA has contributed to the research that led to many innovations in the past that were the result of proper NASA aeronautics research funding in earlier years. The capabilities and efficiencies of component systems have been greatly improved in commercial products because the foundational or fundamental research in earlier years contributed to the improved design of commercial aircraft.

The Decadal Survey had as an assumption that the ranked priorities from its outcome were to be funded within some budget level, a level which was not to be discussed as a part of the charge to the persons who participated in the survey. The earlier 2003 study conducted by the ASME entitled, *"Persistent and Critical Issues in the Nation's Aviation and Aeronautics Enterprise"* (2003), recommended that the NASA aeronautics annual budget be increased to \$2.1B by 2011 in order for the U.S. to remain competitive with international rivals.

AERONAUTICS—UNTIL NOW A GREAT CONTRIBUTOR TO THE U.S. ECONOMY THAT OTHER NATIONS COVET

The U.S. has been the world leader in aeronautics since the Wright Brothers in 1903. As a result of this position of leadership, U.S. military aircraft dominate the skies and the U.S. civil aeronautics industry is the largest positive contributor to the balance of trade. From its inception in 1915, NACA—and later NASA—has invested continuously in aeronautics research and technology, and over the years, academia and industry have come to depend on NASA's investment in long-term research to provide pre-competitive research and screening of high-risk concepts. Using the fundamental NASA research, industry then focuses on product development and implementation.

Many aerospace professionals, like me, know that the U.S. aerospace endeavor is facing serious challenges. The future health and growth of the high wage aerospace industry—which contributes much to a positive balance of trade—critically rests on addressing the concerns raised in the recent report, *"Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future,"* issued by the National Academies of Sciences (NAS) in October 2005. Our international competitors have set their sights on this industry. Competition in the commercial aircraft industry is global in scope. With only a few firms supplying each segment of the market, the actions of one firm significantly affect the actions of its competitors. If international companies receive subsidies that affect pricing and output, this alters the competitive landscape for U.S. industry.

A few years ago the U.S. was the undisputed leader; now the U.S. holds less than 50 percent of the aerospace world market share. The recently released *"Decadal Survey of Civil Aeronautics: Foundation for the Future"* from the National Academies makes a compelling case for the proper support of a wide spectrum of U.S. civil aeronautics research and technology development, if the United States is to remain competitive with other nations in civil aeronautics. Without R&D funding, the research and innovation endeavor shrinks, U.S. technologies become obsolete, our economy shrinks, and the standard of living declines.

As I am sure that you know, the European Vision 2020 focuses on aerospace leadership over the U.S. "In 2020, European leadership will be evident on aircraft throughout the world. The industry in Europe will be the leading developer and supplier of avionics systems and its engines and systems." In 2020 they expect other success. "Such will be the success of the 'European solution' for Air Traffic Management, that a *de facto* world standard will be created." The European Union (EU) plans to invest over 95B Euros ($120B) over the 20 years beginning in 2001. Their goal is to dominate the aeronautics segment, which is largely responsible for the U.S. positive aerospace trade contributions. In addition, Brazil and Canada have increased their support of regional aircraft, which are growing in size and may soon compete with U.S. aircraft.

Investment in the U.S. aeronautics endeavor should be viewed as a national business decision. Currently the U.S. has about $30+ Billion favorable trade balance in the aeronautics sector each year. If we restored the NASA FY07 Aeronautics Budget to its FY 04 level, this would mean that we would be investing three percent to maintain and reap a national aeronautics sector profit of $30 billion. Any businessman would jump at such an opportunity. It is clear that new or improved U.S. products may take a few years to be realized from this investment. However, without this investment there is no possibility to reap benefits from future research. Also, the income taxes on a $30B annual profit should encourage the U.S. Government to invest in the aeronautics research enterprise.

A CRISIS IN R&D FUNDING

Today's national airspace is incapable of meeting the demands of the Next Generation Air Transport System. Critical issues such as the ease of air travel and the speed with which we travel globally continue to threaten the efficiency of civil aviation. Additionally, economic and environmental barriers—as well as the need for critical breakthroughs in technology (such as fuel efficiency, emissions and noise reductions)—must be overcome. The ability for the U.S. to address those—and other—critical issues, and keep the U.S. as the global aeronautics leader is dependent upon appropriate government funding of aeronautics R&D programs, and bolstering the future workforce with the necessary engineering and science education.

Aeronautics R&D has been the key to the success of U.S. industry in the world markets. Other countries are investing considerable public funds in their commercial aircraft industry with the objective of increasing their own product markets. This inevitably takes market share away from U.S. industry. Current proposals to reduce aeronautics R&D funding will continue to harm the already declining U.S. market share.

Without change, the current trend shows a bleak future. U.S. investments in aeronautics R&D continue to decline, thereby placing the U.S. civil aeronautics competitive position at risk. The FY07 NASA aeronautics budget has declined significantly over the past decade from $1.5 billion in FY 1994 to just $724M. The projected budget continues the decline to just $717.6M by FY 2010. This is less than one-third of the $2.1B annual budget recommended by the earlier 2003 study conducted by the ASME entitled, *"Persistent and Critical Issues in the Nation's Aviation and Aeronautics Enterprise"* (2003), in order for the U.S. to remain competitive with international rivals.

Several other practical aspects of research excellence can only be addressed with adequate funding. First, there can be no retreat from a vision that states that NASA aeronautics research will be second to none in the world—EVER. This commitment will attract top NASA and university researchers who will make evolutionary, as well as revolutionary contributions. The power of the thrill of discovery will motivate the next generation of aeronautical and aerospace engineers. A long-term vision and commitment like this will encourage dedicated researchers to devote their careers to excellence and will result in world respected experts. Many of the students at Virginia Tech want to devote their careers to improving airplanes and aeronautical science and technology. They want to have an impact on the future. Give them an exciting vision and resources and the U.S. will not have a future "aerospace work force" problem. Unless they see a future in aeronautics, the lack of an adequate aerospace "work force" will continue.

Discretionary funds at each NASA center and for each branch will allow NASA and grant and contract researchers to pursue some creative ideas that contribute to the mission and goals of that branch, without having all research ideas and topics originating from the top of NASA. Innovative research requires some risk; for example, some small exploratory grants to universities can reveal the merits of new measurement technologies. One cannot always correctly predict what will be discovered in research. In my own research, several turbulent flow phenomena were discovered because we performed original experiments with innovative instrumentation and did not accept the assumptions of conventional wisdom.

DEBATE OVER STRATEGY

Let me first say that I understand the difficulties facing Dr. Lisa Porter and her staff, in managing a program that has been under funded and overshadowed by other NASA priorities. Dr. Porter has done an admirable job in restructuring the research and development infrastructure, in an effort to make a leaner more efficient program, and in an effort to fit R&D demands into budgetary constraints. Several studies have been published over the past 30 months aimed at helping to identify research priorities and problem areas within the NASA aeronautics portfolio. These studies, as well as testimony like you're receiving today, should be reviewed and seriously considered with NASA leadership as a warning shot across the bow of the United States' research and development enterprise. If the U.S. is to remain the world's leader in aeronautics, R&D funding must increase.

The most recent report published was the National Academies of Sciences *"Decadal Study of Aeronautics: Foundation for the Future."* I support the conclusions of the National Academies' study and urge the Administration, Congress, and NASA to consider these recommendations and take actions to appropriately fund them. This report makes a compelling case for the proper support of a wide spectrum of U.S. civil aeronautics research and technology development, if the United States is to remain competitive with other nations in civil aeronautics. Further, the study identifies research areas on which NASA should focus, while also supplying recommendations worth NASA's consideration on partnerships with other federal agencies, universities and private sector stakeholders to accomplish the research goals. As I have said in previous AIAA speaking engagements, capabilities once lost cannot be effectively restored. Even if possible, there are profound financial and human cost penalties. It will take substantially more time, funding and effort to rebuild national capabilities than to maintain these efforts for another year.

The Decadal Study isn't the only report published in the last 18 months tasked to provide a research and development strategy for NASA's aeronautics program. In April 2006, the National Academies published a report entitled, *"Aeronautics Innovation: NASA's Challenges and Opportunities,"* whose findings are supported by AIAA. Again, much like the findings of the Decadal Study, this report called for NASA to prioritize its aeronautics research and development needs, as well work closer with the Nation's aeronautics stakeholders (be they academic, industry or other government agencies). These recommendations are in line with the 2005 recommendations found in the National Institute of Aerospace's *"Responding to the Call: Aviation Plan for American Leadership."* This report is the most comprehensive independent and thorough analysis of federal aeronautics research and development enterprises, and came with several policy recommendations as well as funding requirements. Unfortunately, the report was not well received in Congress due to its length and lofty funding requirements.

Simply stated, NASA must determine a course of action. In 2004, the President issued his *Vision for Space Exploration—the Moon, Mars and Beyond Initiative.* This vision reinvigorating NASA's space program—giving all parties a direction, and a purpose for larger funding initiatives. Thanks to this committee's leadership, along with the support of Rep. Frank Wolf, Congress in last year's appropriation mandated NASA author a National Plan for Aeronautics, the first of its kind.

AIAA expects a national aeronautics R&D policy to provide a clear vision and direction for aeronautics research performed by the Federal Government. As it stands now, aeronautics is a science which provides a sociological as well as economic good for the Nation. However with no clear vision, it is an easy target for funding cuts. A principal challenge for the U.S. aeronautics endeavor is to have sufficient R&D resources sustained over the short- and long-terms in stable programs to remain competitive in the global marketplace. Without R&D funding, the research and innovation endeavor shrinks, US technologies become obsolete, our economy shrinks, and the standard of living declines.

Regarding impact—the correct national plan for aeronautics R&D will be accompanied by a long-term (sustained and reliable) funding commitment from the Executive and Congress, as well as advance U.S. aeronautics technologies to world leadership status in all technical areas. Simply being a competent partner would be a disservice to the Nation. We must strive for excellence.

Finally, a roadmap which includes milestones and meaningful metrics by which we can evaluate possible redundancies and gaps in research programs and capabilities is needed. AIAA is willing to support and/or lead the gathering of relevant metrics.

Below are the specific recommendations AIAA made to the Office of Science and Technology Policy/National Science and Technology Council's Subcommittee on Aeronautics:

- *Roles and Responsibilities*—This policy position should call for the creation of a permanent interagency oversight body to focus on the "big picture" of aeronautics R&D. As it exists today, the national aeronautics enterprise is dysfunctional—with research occurring ad hoc in several federal agencies and private enterprises, often with little interaction with other relevant agencies or research programs. This is a disservice to the Nation as it relates to creating a robust and sustainable aeronautics enterprise within the U.S. This body would be able to aid in the coordination of efforts (and potentially budgets) in an effort to eliminate redundancies in research and strengthen smaller yet important research initiatives. Further, it allows a degree of protection to organizations such as NASA, whose aeronautics programs seem to often lose funding to increase budgets for more entertaining and public interest programs. Coordination is paramount. (NOTE: It is noted that this is a role for the NSTC subcommittee on aeronautics. It is the opinion of AIAA that this effort should not be buried under levels of bureaucracy, but rather raised to the level of the JPDO for example.)
- *Federal R&D Planning and Prioritization*—A biannual review of national aeronautics capabilities and priorities should be conducted. Examples of such reviews already existing within the federal sector are the National Academies Decadal Studies, and the Department of Defense's Quadrennial Review. These are big picture reviews done internally—with external inputs in the process—done in order to be sure that the Nation's capabilities are being directed towards the needed areas of research. To conduct these studies on a biannual basis would allow the NA Decadal Studies to continue every five years, allowing both a long-term and shorter-term ongoing review of the system. This would allow the government to better track its progress, and be able to react to new areas of research as they are invented.
- *Federal vs. Industrial Investment*—It is not the role of this body to draw a clear distinction of the line where federal research should stop, and industrial dollars begin flowing into the process. It is not the role of OSTP to create industrial policy. That said, several trends are troubling. In looking at the complicated issue of large-scale demonstration projects, for example, there are two competing schools of thought. One school of thought believes large-scale demonstrations projects are outdated; data can be collected using computer models and simulations and building block wind-tunnel experiments that validate computer modeling at full scale. This is clearly the approach of the fu-

ture and is much less expensive. However, others feel that for technology to be verified as viable, it must be demonstrated in true environmental conditions—and integrated with all systems. This is a valid approach AFTER new technologies and design tools have been verified and new lower uncertainty designs have been built. Others in research circles also argue that a fundamental piece to conducting research is physical touching, tweaking and immersing oneself in the technology being tested. All of these approaches can be accommodated in a less expensive approach. Clearly this is a complicated issue, one in which panels with industry and end-users would provide more clear examples of where the distinction should be drawn. AIAA can assist in encouraging, sponsoring, and conducting such panels and is willing to do so.

- *Workforce Development*—Many aerospace engineering graduates currently cannot find jobs in the aerospace industry or government, so there is a serious question as to whether there truly is a workforce development issue. This affects the decisions of high school students and undergraduates on enrollment in aerospace programs. Industry and academia already have a functioning and well developed ABET accreditation system for undergraduate degrees in related aeronautical disciplines. Industry has a strong input to the accreditation process and continually makes suggestions about the curricular content of aerospace related disciplines.
    - The existing long proven graduate engineering educational system works in the best U.S. R&D interests when funded and organized properly. Three to five-year grants for faculty and student salary support, equipment and supplies, laboratories, travel, and indirect costs to work on innovative aspects of revolutionary or evolutionary research should be the model. These competitively awarded grants would fit into the mission of the agency and provide for the continued long-term development of faculty expertise and courses, laboratories, and infrastructure that will foster future ideas and developments. (Sporadic funding or funding of U.S. student salaries alone in Fellowships is not generally fruitful. The ideas for future R&D in mature technological areas almost always come from the faculty, not students.)
    - Some in government and industry think erroneously that universities will maintain aerospace curricula and graduate research programs without proper funding. In the face of aeronautical R&D reductions for universities, faculty will and are changing their research interests to subjects where they can obtain their summer salary support, support for their labs, and their students.
    - ITAR issues, and issues on immigration and the United States brain drain also severely hamper U.S. efforts to keep the “best and the brightest” as well as draw the best the world has to offer. While it is not the role of this body to address these issues, they are issues that need addressing by the Federal Government.
- *International Cooperation*—The United States should work to be a leader internationally in aeronautics research and development. That said, we should also strive to be partners with other nations much like the American cooperation within the International Space Station.

IMPACT OF FUNDING ON THE AERONAUTICS WORKFORCE

A healthy NASA workforce, armed with appropriate skills and secure in its future, provides better oversight for technical system procurement and program management. This results in better performing systems, better ability to meet schedule, more productive interactions with other stakeholders in the aerospace enterprise, and more efficient use of taxpayer dollars. Even in the Department of Defense, where procuring complex space systems has been a prime job for several decades, experts are concerned about current government workforce competencies. The May 2003 Final Report of the Defense Science Board (DSB) Task Force on Acquisition of National Security Space Programs, chaired by Tom Young, stated “government capabilities to lead and manage the space acquisition process have seriously eroded.” An organization like NASA, which has been an operational entity for much of recent history and which has less background and experience in development programs, should reasonably expect even greater challenges as it shifts its focus to a development organization and retrains its employees.

In so much as NASA draws employees from among experienced candidates already working in the larger aerospace enterprise, a healthy aerospace enterprise will benefit the NASA workforce. A healthy aerospace enterprise provides a motivated, skilled, and experienced workforce pool from which NASA can draw employees. A healthy aerospace enterprise also provides employment opportunities for NASA employees who desire or need to leave the agency, but still wish to work in the industry.

More aeronautics grants should be awarded competitively to graduate degree granting institutions. The academic research enterprise, which will produce the next generation of aeronautical engineers, is already in distress because of the lack of proper funding. Some aeronautical engineering faculty have left the field because their areas of aeronautics are no longer supported by NASA. Thus, some teachers of the future workforce are leaving the field. Two years ago some grants to universities were abruptly ended with graduate students in the middle of their research, even though the researchers were meeting all goals and requirements.

Graduate fellowships to students alone will not solve the future workforce problem, even though some view this as a less costly way to produce graduate degrees without paying any faculty salaries, lab costs, or indirect costs. Since most of the research ideas come from faculty who dedicate their careers to and are experts in topical areas of research, unless these faculty and their labs are supported, then weak graduates will be produced from out-of-date programs. The faculty will move to research areas where they can obtain stable summer salary support for themselves. Universities cannot afford graduate programs that do not provide sufficient research grant indirect costs and will place resources in other areas than aeronautics.

Further complicating the issues is the age of the American aerospace workforce. The institutional knowledge held in NASA and industry is draining at an alarming rate. The U.S. graduates a fraction of the aerospace engineers graduated by other nations, such as China and India. In 2003, less then 50 percent of the students who received Ph.D.s at American schools were American students. The U.S. must work to retain those within the aeronautics workforce, as well as entice young minds—skeptical about a career in aeronautics—to join the workforce. The only way to do this is make a commitment to investing in long-term research.

DECADAL SURVEY OF CIVIL AERONAUTICS

Foundation for the Future

Steering Committee for the Decadal Survey of Civil Aeronautics

Aeronautics and Space Engineering Board

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*Resigned October 12, 2005.

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Preface

The air transportation system is important to the economic vitality, public well-being, and national security of the United States. The aerospace industry has historically made a large contribution to the positive balance of trade for the U.S. economy. In 2005, it had a $37 billion positive balance of trade, of which $29 billion was for civil aeronautics.[1] In addition, the United States has had a long history as the unchallenged world leader in civil and military aeronautics, though this position is now in jeopardy in areas such as research capability, technological expertise, and the performance of civil aircraft and air traffic management systems.

With leadership comes opportunity, particularly with regard to setting international standards for aircraft certification and operations. A position of continued leadership would allow the United States to ensure that viable global standards continue to be established for the application of emerging technologies and operational concepts. Without such standards the global aviation market and the global transportation system will be fractured into separate fiefdoms ruled by national and regional aviation authorities acting independently. This would impede the ability of passengers and cargo to move seamlessly—and safely—from country to country. The United States needs "world-class science and engineering—not simply as an end in itself, but as the principal means of creating new jobs for its citizenry as a whole as it seeks to prosper in the global marketplace of the 21st century."[2] Strong action is needed to ensure that U.S. leadership continues to assure the future of the domestic and global air transportation systems.[3]

The National Aeronautics and Space Administration (NASA) is explicitly chartered to preserve the role of the United States as a leader in aeronautics technology. To pursue that goal, NASA contracted with the National Research Council s Aeronautics and Space Engineering Board (ASEB) to complete a decadal survey of civil aeronautics, to prioritize research projects to be undertaken in the next 10 years. For the last 50 years, the National Research Council has conducted decadal surveys in astronomy. The idea of conducting a decadal survey of aeronautics originated in discussions among the ASEB, the Office of Management and Budget, and congressional committees with an interest in civil aviation. Although this study takes special note of NASA s priorities for civil aeronautics research, it also identifies national priorities for non-NASA researchers. Additionally, the study points out synergies between civil aeronautics research and research objectives associated with national defense, homeland security, and the space program.

In FY 2004, NASA s budget for aeronautics was just over $1 billion. NASA s aeronautics budget for FY 2006 was $884 million, and it will be reduced to $724 million in FY 2007 if Congress accepts the President s budget. If that happens, in just 3 years NASA s budget for aeronautics will have sustained a reduction of 32 percent, even as NASA s total budget increases by 9 percent. This budgetary trend will make it increasingly difficult for NASA to build a solid foundation for the future. However, regardless of the overall funding level, NASA s aeronautics program should focus on the key strategic objectives,

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[1]D. Napier. 2005. *2005 Year-End Review and 2006 Forecast—An Analysis.* Arlington, Va.: Aerospace Industries Association (AIA). Available online at <www.aia-aerospace.org/stats/yr_ender/yrendr2005_text.pdf>.

[2]National Research Council. 2005. *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future,* p. 30. Washington, D.C.: The National Academies Press. Available online at <http://fermat.nap.edu/catalog/11463.html>.

[3]National Research Council. 2003. *Securing the Future of U.S. Air Transportation: A System in Peril,* p. 11. Washington, D.C.: The National Academies Press. Available online at <http://fermat.nap.edu/catalog/10815.html>.

themes, and high-priority research and technology challenges described herein. The present survey was completed in parallel with ongoing efforts to create a national policy on aviation and separate efforts by NASA Headquarters to assess the aeronautics program. The authors of this report are confident that all three efforts will work toward the common goal of assuring that long-term national investments in aeronautics research and technology substantially improve the air transportation system and achieve other appropriate national objectives.

Paul Kaminski, *Chair*
Decadal Survey of Civil Aeronautics Steering Committee

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the Report Review Committee of the National Research Council (NRC). The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Tony Broderick, Aviation Safety Consultant
Dianne Chong, The Boeing Company
Raymond Colladay, Lockheed Martin Astronautics (retired)
John Douglass, Aerospace Industries Association of America
Alan Epstein, NAE, Massachusetts Institute of Technology
Kenneth Rosen, NAE, General Aero-Science Consultants, LLC
David Schmidt, University of Colorado
Gunter Stein, NAE, Honeywell (retired)
Tom Williams, Northrop Grumman

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Sheila E. Widnall, NAE, Massachusetts Institute of Technology. Appointed by the NRC, she was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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Executive Summary

The U.S. air transportation system is a key contributor to the economic vitality, public well-being, and national security of the United States. The next decade of U.S. civil aeronautics research and technology (R&T) development should provide a foundation for achieving four high-priority Strategic Objectives:

- Increase capacity.
- Improve safety and reliability.
- Increase efficiency and performance.
- Reduce energy consumption and environmental impact.

Civil aeronautics R&T should also consider two lower-priority Strategic Objectives:

- Take advantage of synergies with national and homeland security.
- Support the space program.

The purpose of the Decadal Survey of Civil Aeronautics is to develop a foundation for the future—a decadal strategy for the federal government s involvement in civil aeronautics, with a particular emphasis on the National Aeronautics and Space Administration s (NASA s) research portfolio. A quality function deployment (QFD) process was used to identify and rank 89 R&T Challenges in relation to their potential to achieve the six Strategic Objectives listed above.[1] That process produced a list of 51 high-priority R&T Challenges that must be overcome to further the state of the art (see Table ES-1). These high-priority Challenges are equally divided among five R&T Areas:

- Area A: Aerodynamics and aeroacoustics.
- Area B: Propulsion and power.
- Area C: Materials and structures.
- Area D: Dynamics, navigation, and control, and avionics.
- Area E: Intelligent and autonomous systems, operations and decision making, human integrated systems, and networking and communications.

Advances in these Areas would have a significant, long-term impact on civil aeronautics. Accordingly, federal funds, facilities, and staff should be made available to advance the high-priority R&T Challenges in each Area.

Five Common Themes summarize threads of commonality among the 51 high-priority R&T Challenges:

- Physics-based analysis tools to enable analytical capabilities that go far beyond existing modeling and simulation capabilities and reduce the use of empirical approaches.
- Multidisciplinary design tools to integrate high-fidelity analyses with efficient design methods and to accommodate uncertainty, multiple objectives, and large-scale systems.
- Advanced configurations to go beyond the ability of conventional technologies and aircraft to achieve the Strategic Objectives.
- Intelligent and adaptive systems to significantly improve the performance and robustness of aircraft and the air transportation system as a whole.
- Complex interactive systems to better understand the nature of and options for improving the performance of the air transportation system, which is itself a complex interactive system.

These Themes are not an end in themselves; they are a means to an end. Each Theme describes enabling approaches that will contribute to overcoming multiple Challenges in the five R&T Areas. Exploiting the synergies identified in each

[1] QFD is a group decision-making methodology often used in product design.

TABLE ES-1 Fifty-one Highest Priority Research and Technology Challenges for NASA Aeronautics, Prioritized by R&T Area

A Aerodynamics and Aeroacoustics	B Propulsion and Power	C Materials and Structures	D Dynamics, Navigation, and Control, and Avionics	E Intelligent and Autonomous Systems, Operations and Decision Making, Human Integrated Systems, Networking and Communications
A1 Integrated system performance through novel propulsion–airframe integration	B1a Quiet propulsion systems	C1 Integrated vehicle health management	D1 Advanced guidance systems	E1 Methodologies, tools, and simulation and modeling capabilities to design and evaluate complex interactive systems
A2 Aerodynamic performance improvement through transition, boundary layer, and separation control	B1b Ultraclean gas turbine combustors to reduce gaseous and particulate emissions in all flight segments	C2 Adaptive materials and morphing structures	D2 Distributed decision making, decision making under uncertainty, and flight-path planning and prediction	E2 New concepts and methods of separating, spacing, and sequencing aircraft
A3 Novel aerodynamic configurations that enable high performance and/or flexible multi-mission aircraft	B3 Intelligent engines and mechanical power systems capable of self-diagnosis and reconfiguration between shop visits	C3 Multidisciplinary analysis, design, and optimization	D3 Aerodynamics and vehicle dynamics via closed-loop flow control	E3 Appropriate roles of humans and automated systems for separation assurance, including the feasibility and merits of highly automated separation assurance systems
A4a Aerodynamic designs and flow control schemes to reduce aircraft and rotor noise	B4 Improved propulsion system fuel economy	C4 Next-generation polymers and composites	D4 Intelligent and adaptive flight control techniques	E4 Affordable new sensors, system technologies, and procedures to improve the prediction and measurement of wake turbulence
A4b Accuracy of prediction of aerodynamic performance of complex 3-D configurations, including improved boundary layer transition and turbulence models and associated design tools	B5 Propulsion systems for short takeoff and vertical lift	C5 Noise prediction and suppression	D5 Fault-tolerant and integrated vehicle health management systems	E5 Interfaces that ensure effective information sharing and coordination among ground-based and airborne human and machine agents
A6 Aerodynamics robust to atmospheric disturbances and adverse weather conditions, including icing	B6a Variable-cycle engines to expand the operating envelope	C6a Innovative high-temperature metals and environmental coatings	D6 Improved onboard weather systems and tools	E6 Vulnerability analysis as an integral element in the architecture design and simulations of the air transportation system
A7a Aerodynamic configurations to leverage advantages of formation flying	B6b Integrated power and thermal management systems	C6b Innovative load suppression, and vibration and aeromechanical stability control	D7 Advanced communication, navigation, and surveillance technology	E7 Adaptive ATM[a] techniques to minimize the impact of weather by taking better advantage of improved probabilistic forecasts
A7b Accuracy of wake vortex prediction, and vortex detection and mitigation techniques	B8 Propulsion systems for supersonic flight	C8 Structural innovations for high-speed rotorcraft	D8 Human–machine integration	E8a Transparent and collaborative decision support systems
A9 Aerodynamic performance for V/STOL and ESTOL, including adequate control power	B9 High-reliability, high-performance, and high-power-density aircraft electric power systems	C9 High-temperature ceramics and coatings	D9 Synthetic and enhanced vision systems	E8b Using operational and maintenance data to assess leading indicators of safety
A10 Techniques for reducing/ mitigating sonic boom through novel aircraft shaping	B10 Combined-cycle hypersonic propulsion systems with mode transition	C10 Multifunctional materials	D10 Safe operation of unmanned air vehicles in the national airspace	E8c Interfaces and procedures that support human operators in effective task and attention management
A11 Robust and efficient multidisciplinary design tools				

[a]ATM, air traffic management; V/STOL, vertical and/or short takeoff and landing; ESTOL, extremely short takeoff and landing.

Common Theme will enable NASA s aeronautics program to make the most efficient use of available resources.

Even if individual R&T Challenges are successfully overcome, two key barriers must also be addressed before the Strategic Objectives can be accomplished:

- *Certification.* As systems become more complex, methods to ensure that new technologies can be readily applied to certified systems become more difficult to validate. NASA, in cooperation with the Fedeal Aviation Administration (FAA), should anticipate the need to certify new technology before its introduction, and it should conduct research on methods to improve both confidence in and the timeliness of certification.
- *Management of change, internal and external.* Changing a complex interactive system such as the air transportation system is becoming more difficult as interactions among the various elements become more complex and the number of internal and external constraints grows. To effectively exploit R&T to achieve the Strategic Objectives, new tools and techniques are required to anticipate and introduce change.

This report also encourages NASA to do the following:

- Create a more balanced split in the allocation of aeronautics R&T funding between in-house research (performed by NASA engineers and technical specialists) and external research (by industry and/or universities). As of January 2006, NASA seemed intent on allocating 93 percent of NASA s aeronautics research funding for in-house use.
- Closely coordinate and cooperate with other public and private organizations to take advantage of advances in cross-cutting technology funded by federal agencies and private industry.
- Develop each new technology to a level of readiness that is appropriate for that technology, given that industry s interest in continuing the development of new technologies varies depending on urgency and expected payoff.
- Invest in research associated with improved ground and flight test facilities and diagnostics, in coordination with the Department of Defense and industry.

The eight recommendations formulated by the steering committee and set forth in Box ES-1 summarize action necessary to properly prioritize civil aeronautics R&T and achieve the relevant Strategic Objectives. This report should provide a useful foundation for the ongoing effort in the executive branch to develop an aeronautics policy. In addition, even though the scope of this study purposely did not include specific budget recommendations, it should support efforts by Congress to authorize and appropriate the NASA aeronautics budget.

BOX ES-1
Recommendations to Achieve Strategic Objectives for Civil Aeronautics Research and Technology

1. NASA should use the 51 Challenges listed in Table ES-1 as the foundation for the future of NASA s civil aeronautics research program during the next decade.
2. The U.S. government should place a high priority on establishing a *stable* aeronautics R&T plan, with the expectation that the plan will receive sustained funding for a decade or more, as necessary, for activities that are demonstrating satisfactory progress.
3. NASA should use five Common Themes to make the most efficient use of civil aeronautics R&T resources:
   - Physics-based analysis tools
   - Multidisciplinary design tools
   - Advanced configurations
   - Intelligent and adaptive systems
   - Complex interactive systems
4. NASA should support fundamental research to create the foundations for practical certification standards for new technologies.
5. The U.S. government should align organizational responsibilities as well as develop and implement techniques to improve change management for federal agencies and to assure a safe and cost-effective transition to the air transportation system of the future.
6. NASA should ensure that its civil aeronautics R&T plan features the substantive involvement of universities and industry, including a more balanced allocation of funding between in-house and external organizations than currently exists.
7. NASA should consult with non-NASA researchers to identify the most effective facilities and tools applicable to key aeronautics R&T projects and should facilitate collaborative research to ensure that each project has access to the most appropriate research capabilities, including test facilities; computational models and facilities; and intellectual capital, available from NASA, the Federal Aviation Administration, the Department of Defense, and other interested research organizations in government, industry, and academia.
8. The U.S. government should conduct a high-level review of organizational options for ensuring U.S. leadership in civil aeronautics.

1

Introduction

IMPORTANCE OF U.S. CIVIL AVIATION

Aviation plays an important role in supporting the preeminent economic, political, and military positions of the United States. U.S. air carriers move more passengers and cargo than those of any other country. U.S. industry is also a leader in manufacturing aircraft and air traffic management (ATM) systems. Globally, the United States has more general aviation and business aircraft than the rest of the world combined (GAMA, 2000, and Lubitz, 1997). In addition, far more commercial air transportation operations occur within the United States than within any other country. The size and efficiency of the U.S. air transportation system help the United States compete in the global economy by providing a transportation infrastructure that often responds quickly to changes in market demand and the various needs of the public, industry, and government at all levels (national, state, and local). An efficient air transportation system enables the rest of the economy to benefit from the efficiencies of just-in-time manufacturing. Seamless links between U.S. and global air transportation systems enable U.S. manufacturers to operate efficiently even with global supply chains, and it allows foreign manufacturers to include U.S. suppliers in their supply chains. Air cargo also helps e-commerce live up to its potential by delivering goods quickly. However, U.S. manufacturers share of the global market for civil aeronautics is shrinking in the face of foreign competition. Aviation is a technology-intensive field, and maintaining global leadership will be impossible without continued investments in research and technology (R&T) by government and industry.

The air transportation system includes passenger and cargo airlines; general aviation, including business aviation; and the national airspace system, including airports, ATM facilities, and operational elements of the Federal Aviation Administration (FAA). U.S. civil aviation includes all of the above, plus manufacturers and research organizations in government, industry, and academia. Civil aviation benefits the United States in terms of the economy, public well-being, and national security, including homeland security. An affordable air transportation system makes the short travel times of aviation readily available to business and leisure travelers, improving the quality of life for all who choose to travel by air or who benefit from quick delivery of air freight. However, for the purpose of this report, the primary mission of the air transportation system, which is to provide efficient air transportation, is considered to be distinct from the national security and homeland security missions of the Department of Defense (DoD) and the Department of Homeland Security (DHS), respectively.

Growth in air travel comes at a cost in terms of noise for residents of communities around airports and in terms of aircraft emissions locally, regionally, and globally. Aeronautics R&T has reduced the noise and emissions produced by individual aircraft and has significantly reduced the total environmental impacts compared to what they would have been without new aircraft that are quieter, more efficient, and create fewer emissions than earlier generations. Advanced technologies have also substantially improved safety, so that even with substantial increases in air travel, accidents involving large civil transports tend to be increasingly infrequent. Even so, additional research is needed to discern, monitor, and eliminate or reduce the underlying causes and other factors that contribute to aircraft accidents. In addition, research can continue to reduce the environmental impact of individual aircraft, it can offset the environmental impact of increases in domestic and global air travel, and it may even reduce the local, regional, or global impact of air transportation, despite continued growth in air travel. Although the performance of large civil transports is of primary interest to the overall operation of the air transportation system, research can also address issues with other classes of aircraft. For example, the accident rate of general aviation aircraft is much higher than the accident rate of large civil transports, and the high noise levels of rotorcraft inhibit their ability to increase the capacity of the air transportation system.

In decades past, advances in military aviation were the source of many advances in civil aviation, most notably the swept-wing jet transport. More recently, military aviation R&T development funds have been reduced, and the rate at which new military aircraft are developed has greatly declined. In some cases, advances in civil aviation are being transferred to military applications, and dominance of the skies will be greatly affected by the results of civil aeronautics research. A more capable air transportation system could also enhance homeland security. For example, a next-generation air transportation system that uses a network-based approach to communications and the exchange of information would allow surveillance data collected from various air traffic sensors to provide the same comprehensive operational picture to all systems users and monitors, including the DHS and the North American Aerospace Defense Command. The air transportation system of the future should also accommodate routine operations of unmanned air vehicles (UAVs), which are taking an ever larger role in military aviation and will likewise be important to homeland security.

U.S. civil aviation is too important to allow the future to be defined solely by short-term market forces, which are unlikely to produce an efficient system that responds appropriately to user needs. Individual elements of the U.S. air transportation system are owned and operated by competitive companies, government agencies, and private citizens, each with their own motivations, resources, and limitations. Today and in the future, the U.S. air transportation system will not be able to meet the expectations of government, industry, and the public unless ATM equipment and procedures—which generally are owned, controlled, and operated by the federal government—are designed, implemented, and operated as efficiently as possible. In addition, market forces do not provide individual companies with a positive return on investments for research in many areas that are important to public well-being, such as safety, noise, emissions, speed, and basic research. Companies cannot make a business case for supporting an appropriate level of research in these areas, especially when the risk is high and/or a long research program is required to develop commercial applications. NASA, the FAA, and other government agencies must support key noncompetitive and precompetitive research to ensure that the U.S. air transportation system continues to benefit the United States. This is consistent with traditional practices of the FAA and NASA and the legislative charters for these agencies.

PERSPECTIVES

The U.S. air transportation system can be viewed from four perspectives:

- *Operational.* How does the system function in terms of different phases of operation (takeoff, en route, approach, and landing) and different geographical areas of operation?
- *Aircraft and ground systems.* What are the effects on the overall system of changes in the design and performance of individual aircraft and ground facilities, as well as the systems and subsystems that are incorporated within and among various aircraft and facilities?
- *Organizational.* How do manufacturers, airlines, pilots, controllers, customers, regulators, and other stakeholders (some with common interests and some with conflicting interests) function together to operate the air transportation system of today and to develop the air transportation system of the future? Also, how well does the current and future air transportation system meet the needs of stakeholders, individually and collectively?
- *International.* How does the U.S. air transportation system interact with a global economy, international aviation authorities, and international corporations that are interactive, interdependent, and integrated?

Efforts to improve the existing air transportation system—and to develop the next-generation air transportation system—should take a holistic approach that integrates all of the above perspectives and recognizes that the U.S. air transportation system is a complex interactive system that is more than the sum of its parts.[1]

ORIGIN OF THE STUDY

For the last 50 years, the National Research Council (NRC) has conducted decadal surveys in astronomy, prioritizing research projects to be undertaken in the next 10 years.[2] When the latest astronomy survey was released in 2001 (NRC, 2001), all of the large and many of the moderate-sized programs recommended in the preceding report (NRC, 1991) had been enacted. More recently, NASA commissioned additional decadal surveys in the fields of solar and space physics (NRC, 2003a), planetary science (NRC, 2003c), and Earth science (NRC, 2005). The recently

[1]As used in this report, complex interactive systems (or a system of systems) refer to adaptive systems consisting of a large, widespread collection or network of independent systems functioning together to achieve a common purpose. Complex interactive systems are distinguished from large, monolithic systems by the independent functioning of their components, which provides freedom for existing components to evolve and new components to emerge independent of a central configuration control authority. Complex interactive systems also tend to be distributed over a large geographic extent and require effective communications and coordination protocols for the various components to interact efficiently (Maier, 2006).

[2]The research strategies outlined in these reports are decadal surveys in the sense that they are based on thoughtful examinations of research requirements over the subsequent 10 years.

launched and highly publicized mission to Pluto was consistent with the recommendations contained in the 2003 planetary science decadal survey.

The idea of conducting a decadal survey of aeronautics originated in discussions among the NRC s Aeronautics and Space Engineering Board, the Office of Management and Budget, and congressional committees with an interest in civil aviation. Recognizing the potential value of such a study, NASA subsequently contracted with the Aeronautics and Space Engineering Board to carry out the study. Although the study focuses on civil aviation, it recognizes and calls out specific synergies that exist with national defense, homeland security, and the space program.

PURPOSE OF THE SURVEY

As detailed in Appendix G, the purpose of the Decadal Survey of Civil Aeronautics was to develop a decadal strategy for federal aeronautics research. The NRC was charged by NASA with providing guidelines for investment in aeronautics R&T, with a particular emphasis on NASA s research portfolio in each of five R&T Areas:

- Area A: Aerodynamics and aeroacoustics.
- Area B: Propulsion and power.
- Area C: Materials and structures.
- Area D: Dynamics, navigation, and control, and avionics.
- Area E: Intelligent and autonomous systems, operations and decision making, human integrated systems, and networking and communications.

The NRC appointed five panels, each with the expertise necessary to examine one of these Areas, along with a steering committee to oversee the work of the panels and prepare this report based on inputs from the panels as well as information gathered directly by the steering committee. The membership of the steering committee included the five panel chairs and one other member of each panel (see Appendix H).

This report describes research necessary to further the state of the art in the five R&T Areas (see Chapter 3). Advances in these Areas would have a significant long-term impact on national aeronautics, and research in these Areas is consistent with NASA s legislative charter, as described in the National Aeronautics and Space Act of 1958, as amended. Accordingly, federal funds, facilities, and staff should be made available to advance each Area.

This report also includes guidance on how federal resources allocated for aeronautics research should be distributed between in-house and external organizations, how aeronautics research can take advantage of advances in cross-cutting technology funded by federal agencies and private industry, and how far along the development and technology readiness path federal agencies should advance key aeronautics technologies, and it provides a set of overall findings and recommendations to provide a cumulative, integrated view of civil aeronautics research challenges and priorities (see Chapter 5). Lessons learned from other federal agencies appear in Appendix F. In accordance with the statement of task, this report does not include specific budget recommendations.

STRATEGIC OBJECTIVES FOR U.S. CIVIL AERONAUTICS RESEARCH

The existence of an explicit national aeronautics policy on R&D would have greatly facilitated the formulation of an aeronautics research strategy, because it would have defined the strategic objectives that should be used to shape future aeronautics research. In the absence of a stated national aeronautics policy, the steering committee identified and defined six Strategic Objectives that should motivate and guide the next decade of civil aeronautics research in the United States:[3]

- Capacity.
- Safety and reliability.
- Efficiency and performance.
- Energy and the environment.
- Synergies with national and homeland security.
- Support to space.

Capacity is the maximum amount of people and goods that can be moved through the air transportation system per unit time regardless of environmental conditions. The air transportation system of the future will need to double capacity over the next 10 to 35 years (NRC, 2003b).[4]

Safety and reliability refer to the ability of the air transportation system to meet expectations with regard to reductions in fatalities, injuries, loss of goods, and equipment damage or malfunction. The risk of accidents must be continually reduced so that the number of accidents will remain steady or decrease even as the number of flight operations increases substantially.

Efficiency and performance refer to achieving maximum utilization of the air transportation system so that available resources (aircraft, facilities, fuel, etc.) can provide as much service as possible (moving aircraft, passengers, and cargo). This requires an air transportation system with enhanced capabilities that improve mobility, access, and flexibility and reduce travel time and costs. The goal is to increase substantially air transportation system capacity per unit resource.

[3]Strategic Objectives and other key terminology used in this report are described in Box 1-1 and illustrated in Figure 1-1.

[4]This range of outcomes is equivalent to annual growth rates of 2.0 to 7.2 percent. An annual growth rate of 7.2 percent would double demand in 10 years, triple demand in 15 years, quadruple demand in 20 years, and increase demand sixfold in 25 years.

BOX 1-1
Terminology

This report uses the following terminology to create the framework for a decadal plan for civil aeronautics:

- *R&T Area.* Five Areas were identified that encompassed the R&T of greatest relevance to the air transportation system (see Chapter 2).
- *R&T Challenge.* For each Area, a set of key Challenges was identified and prioritized (see Chapter 3).
- *Strategic Objective.* The Strategic Objectives described in the first section of this chapter were used as the primary criteria for assessing the national importance of each R&T Challenge.
- *Why NASA?* Four criteria (supporting infrastructure, mission alignment, lack of alternative sponsorship, and appropriate level of risk) were used to determine how appropriate it is for NASA to address each R&T Challenge. The scores assigned to these four criteria were averaged to create a single "Why NASA?" score for each Challenge.
- *R&T Thrust.* Thrusts describe threads of commonality among R&T Challenges within each Area (see Chapter 3).
- *Common Theme.* Common Themes are used to group cross-cutting Challenges from more than one R&T Area (see Chapter 4). These Themes do not encompass all the high-priority Challenges, because some high-priority Challenges did not have closely linked challenges in other Areas.
- *Milestone.* Milestones for each Challenge are included in the detailed descriptions that appear in Appendixes A through E. These milestones are intended to indicate levels of achievement that demonstrate important advances in capability rather than detailed programmatic progress.

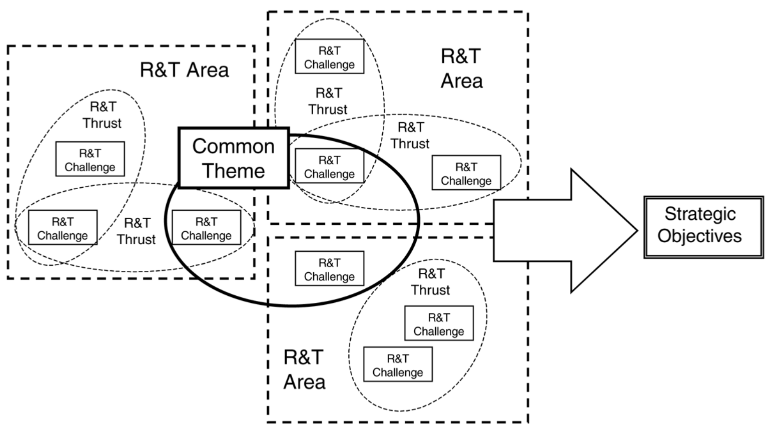

FIGURE 1-1 Terminology breakdown tree.

Energy and the environment refer to minimizing the negative impact of air transportation on Earth, its atmosphere, and its natural resources. This objective also includes the search for alternative fuels should petroleum-derived fuels become a constraint on air transportation. The goal is to reduce noise, emissions, and hazardous waste products (such as coolants and retired aircraft components), as well as fuel use per passenger seat mile and cargo ton mile.

Synergy with national and homeland security refers to the added value of specific aeronautical research when it helps to achieve the first four goals while also helping to achieve the goals of the DoD and the DHS. Because the steering committee had to define priorities for aeronautics R&T at NASA, this report focuses on civil rather than national or homeland security aeronautics research. This objective acknowledges that a great deal of civil aeronautics research also has national and homeland security applications. The goal is to transfer research results to DoD and DHS, as appropriate.

Support to space refers to the added value of specific aeronautical research if it helps to achieve the first four Strategic Objectives while also helping to achieve the goals of NASA s space program, including access to space, space exploration, reentry, and aeronautics as they relate to the performance of vehicles in non-Earth atmospheres. Results of research on relevant topics, such as hypersonics and operations in extreme (or alien) environments, would be transferred to NASA s space program.

The future of the air transportation system should be guided by quantifiable goals (NRC, 2003b). The federal government, however, does not have quantifiable goals related to the Strategic Objectives. Quantifiable goals are included in the strategic research agenda that is guiding aeronautics research in Europe. For example, European research goals for 2020 include the following (ACARE, 2004):

- Reduce fuel consumption and CO_2 emissions by 50 percent.
- Reduce perceived external noise by 50 percent.
- Reduce oxides of nitrogen (NO_x) by 80 percent.

Goals unsupported by funded and approved R&T programs, however, are little more than aspirations, and U.S. efforts to define quantifiable goals for the future should be coordinated with R&T planning efforts to reach the desired end state, consisting of credible goals and a properly directed R&T program.

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2

Process for Integration and Prioritization

STUDY PROCESS

The study began in September 2005 with a joint kick-off meeting between the steering committee and its supporting panels in order to hear directly from NASA and other federal entities the primary purpose of the study. Committee and panel members were also briefed on a recent report of the National Institute of Aerospace (NIA, 2005) and an earlier NRC study, *Aeronautical Technologies for the Twenty-first Century* (NRC, 1992).

At the second steering committee meeting, in November 2005, representatives from industry and academia were consulted in a roundtable discussion. The steering committee then developed a framework for the study, Strategic Objectives, and guidelines for the panels. It developed a quality function deployment (QFD) process, described below, for the panels to use. It identified, defined, and weighted the Strategic Objectives as well as the Why NASA? criteria. Finally, it outlined some basic rules and conventions for completing the prioritization process, all of which are summarized below.

From November 2005 through January 2006, each panel held a series of meetings. The panels identified and consulted a broad range of experts with backgrounds in industry, government, and academia. Many of them were able to attend panel meetings (see Appendix I). Working among themselves, the panel members then developed lists of research topics, called R&T Challenges. In some cases, these lists were very long, exceeding 100 items for a single R&T Area. Because it was not feasible to describe and prioritize so many Challenges in detail, the panels winnowed their lists, first by dropping those that seemed to have very little relevance to the Strategic Objectives. The number of Challenges was further reduced (to a total of 89 among all five Areas) by increasing the breadth of many of them, so that several very specific R&T topics could be collected into a single Challenge. Each panel, working under the oversight of the Steering Committee, then used the QFD methodology to relate these Challenges to the Strategic Objectives, generating a list of the 10 highest-priority Challenges within their Area.[1] All five panels considered issues related to subsonic, supersonic, and hypersonic flight regimes; infrastructure; transformation of the air transportation system; workforce; and education.

At the final meeting of the steering committee, in February 2006, it compiled inputs from the panels, vetted the prioritized list for each R&T Area, resolved conflicts in scoring among panels that had considered similar technologies, identified common themes among R&T Challenges from more than one R&T Area, and reached consensus on the overall content of the report, including summary findings and recommendations.

PRIORITIZATION

The steering committee directed the panels to use a modified QFD approach to rank the R&T Challenges they identified. QFD is a group decision-making methodology often used in product design. It is very useful for evaluating choices given a specific set of values. Cross-cutting research tends to rank highly, because it helps achieve multiple Objectives. The QFD scores described in this report for each R&T Challenge have no absolute, quantitative value. Rather, the QFD process serves as an organizational system that consistently evaluates each R&T Challenge and clearly conveys the rationale for the priority assigned to it. It is a qualitative process that utilizes the judgments and wisdom of informed experts to achieve a collective ranking of disparate objects.

[1]As noted in Chapter 3, the 11 highest-priority Challenges are identified for R&T Area A.

National Priority

The QFD process for this study used a matrix like the one shown in Table 2-1. The primary evaluation criteria are the six Strategic Objectives.[2] The R&T Challenges to be prioritized appear in the left-hand rows.[3] Each panel, as a group, scored each R&T Challenge with respect to the individual Objectives, based on its relevance and impact. Possible scores are limited to 1, 3, or 9. As is often done in QFD exercises, a nonlinear scale is used to magnify the differences in technologies to help delineate the most critical ones. A score of 1 implies that the Challenge has little or no relevance to the Objective. A 3 implies that the Challenge has moderate relevance and impact. A 9 implies that the Challenge has major relevance and impact.

The steering committee assigned each of the six Strategic Objectives a weight of 1, 3, or 5 to convey its relative importance to U.S. civil aeronautics research. The committee believes that the first two Objectives, capacity and safety and reliability, are the most critical because of their broad impact on the air transportation system as a whole, the vital importance of safety, and need to meet growing demand, and assigned them a weight of 5. The next two Objectives, efficiency and performance and energy and the environment, directly affect certain stakeholders and indirectly affect the public as a whole through their secondary effects on capacity and safety and reliability. They are considered to be slightly less important overall and are assigned a weight of 3. Finally, synergy with national and homeland security and support to space are assigned a weight of 1. Neither of these Objectives falls directly under the purview of civil aeronautics. Even so, security and the space program are important to the nation, and all other things being equal, civil aeronautics research that also provides benefits for these two Objectives should be of somewhat higher priority than comparable research that does not provide benefits for them.

The weight for each Strategic Objective (1, 3, or 5) is multiplied by the relevance and impact score (1, 3, or 9), which describes the impact on that Objective of research in a particular R&T Challenge. The sum of those products for each R&T Challenge then becomes the national priority score for that R&T Challenge. That score is a measure of the relative overall value to the nation of conducting research to overcome that particular R&T Challenge.

NASA Priority

Every R&T Challenge that has a high national priority does not necessarily become a high priority for NASA s civil aeronautics research program. To determine the NASA priority scores, each R&T Challenge is given a Why NASA? score, which is multiplied by the national priority score to arrive at a NASA priority. The Why NASA? score for each R&T Challenge is the average of the scores (1, 3, or 9) in the four Why NASA? columns on the right-hand side of the QFD tables. These scores evaluate each R&T Challenge in terms of the following:

- Supporting infrastructure
- Mission alignment
- Lack of alternative sponsors
- Appropriate level of risk

The scores used to assess priorities are based on the current situation, which will change. For example, this study did not attempt to predict how NASA expertise and facilities in various areas might degrade or mature, how NASA s aeronautics mission might be redefined, how the priorities of other research organizations might change, or how advances in the state of the art might change the risk associated with specific R&T Challenges. Changes in any of these factors will change the Why NASA? scores, which will directly change the NASA priority scores.

Supporting infrastructure

Supporting infrastructure refers to whether NASA already possesses the facilities, resources, and expertise to conduct research related to an R&T Challenge. A score of 1 implies that NASA has little or no relevant infrastructure. A score of 3 implies that NASA has infrastructure that is relevant but not unique. That is, industry, academia, or non-NASA federal agencies possess similar infrastructure or could obtain it easily. A score of 9 implies that NASA has infrastructure that is both relevant and unique.

Mission alignment

Mission alignment refers to whether research related to the R&T Challenge falls under NASA s charter, as defined in the National Aeronautics and Space Act of 1958 (As Amended). Relevant portions of the Space Act appear in Box 2-1. A score of 1 implies that the Challenge has little or no relevance to any item in the charter. A score of 3 implies that it has some relevance to and impact on one item in the char-

[2]The QFD matrix used in this study (see Table 2-1 and the QFD matrices in Chapter 3) is a simplified form of the table (sometimes called a house of quality) that is used in a standard QFD assessment. The QFD matrix for this study has also been rotated 90 degrees from the orientation normally used to display a QFD table. The Strategic Objectives in this study take the place of the customer requirements that appear in a standard QFD table, the R&T Challenges take the place of key product and process characteristics, and the Why NASA? composite score takes the place of risk level. The national priority scores are equivalent to the absolute importance rankings in a standard QFD table, and the NASA priority scores are equivalent to risk-weighted importance.

[3]Each Challenge is designated by the letter of the Area to which is belongs and by its NASA priority ranking in that Area. Thus, the R&T Challenge with the highest NASA priority in the aerodynamics and aeroacoustics R&T Area is designated A1. If two Challenges in that Area were to tie for second place, they would be listed alphabetically and designated A2a and A2b, and the next highest priority Challenge would be designated A4.

TABLE 2-1 Sample QFD Prioritization

	Strategic Objective							Why NASA?					
	Capacity	Safety and Reliability	Efficiency and Performance	Energy and the Environment	Synergies with Security	Support to Space	National Priority	Supporting Infrastructure	Mission Alignment	Lack of Alternative Sponsors	Appropriate Level of Risk	Why NASA Composite Score	NASA Priority Score
R&T Challenge Weight	5		3		1			1/4 each					
X1 R&T Challenge 1	9	9	3	3	1	1	110	3	9	3	9	6.0	660
X2 R&T Challenge 2	3	9	3	9	1	1	98	1	9	3	9	5.5	539
X3 R&T Challenge 3	1	1	1	3	9	9	40	9	9	9	9	9.0	360

BOX 2-1
NASA s Mission as Reflected by Selected Items from the National Aeronautics and Space Act of 1958 (As Amended)

Section 102. Declaration of policy and purpose

(d) The aeronautical and space activities of the United States shall be conducted so as to contribute materially to one or more of the following objectives:

(1) The expansion of human knowledge of the Earth and of phenomena in the atmosphere and space;
(2) The improvement of the usefulness, performance, speed, safety, and efficiency of aeronautical and space vehicles;
(3) The development and operation of vehicles capable of carrying instruments, equipment, supplies, and living organisms through space;
(4) The establishment of long-range studies of the potential benefits to be gained from, the opportunities for, and the problems involved in the utilization of aeronautical and space activities for peaceful and scientific purposes;
(5) The preservation of the role of the United States as a leader in aeronautical and space science and technology and in the application thereof to the conduct of peaceful activities within and outside the atmosphere;
(6) The making available to agencies directly concerned with national defense of discoveries that have military value or significance, and the furnishing by such agencies, to the civilian agency established to direct and control nonmilitary aeronautical and space activities, of information as to discoveries which have value or significance to that agency;
(7) Cooperation by the United States with other nations and groups of nations in work done pursuant to this Act and in the peaceful application of the results thereof;
(8) The most effective utilization of the scientific and engineering resources of the United States, with close cooperation among all interested agencies of the United States in order to avoid unnecessary duplication of effort, facilities, and equipment; and
(9) The preservation of the United States preeminent position in aeronautics and space through research and technology development related to associated manufacturing processes.

ter. A score of 9 implies that the Challenge has great relevance to and impact on at least one item in the charter or some relevance to and impact on multiple items.

Lack of alternative sponsors

Lack of alternative sponsors refers to whether other sponsors are able and willing to perform the necessary research. NASA should not be repeating research that is (or should be) done by others. A score of 1 implies that if NASA did not do the research, some other organization would do it, or does already. A score of 3 implies that if NASA did not do the research, it would be done but not be developed to an adequate level of maturity, or it would lack aeronautical focus. A score of 9 implies that if NASA did not do the research, it would not be done.

Appropriate level of risk

Appropriate level of risk refers to whether the level of risk associated with an R&T Challenge is appropriate for a NASA research project. For example, NASA should not pursue incremental research that is of such low risk that industry could easily complete the research. Nor should NASA pursue research of great theoretical promise if the scientific and technical hurdles are so high that it has very little chance of success. A score of 1 implies that the Challenge is either very low risk (such that industry could pursue it) or extremely high risk (such that there is only a small chance of seeing any benefit without unforeseen revolutionary breakthroughs). A score of 3 implies that the Challenge either has low risk or very high risk. A score of 9 implies that it has moderate to high risk, which is a good fit to NASA s level of risk tolerance. All NASA research should be expected to progress toward established goals, but innovation is not possible without tolerance for failure, and the pursuit of moderate- and high-risk technology is appropriate for the nation s center of excellence for aeronautics.

NEXT STEPS

The top 10 R&T Challenges for each Area, in priority order, are discussed in Chapter 3. All the Challenges are discussed in Appendixes A to E, which also contain specific milestones. The technical discussions and milestones included in this report are intended to be advisory, as it was not feasible to complete a rigorous, comparative assessment of all of the research options that might be associated for each of the 89 Challenges. The committee believes that the best approach for selecting specific research projects to fund would be for NASA to solicit proposals from industry and academia at the level of the individual Challenges.

Comparing Priorities Among Different R&T Areas

The QFD process appears to be a rigorous quantitative process, with strict, laid-out criteria for each score. However, while each panel could consistently distinguish between what deserves a 3 and what deserves a 9, for example, some variations from panel to panel were inevitable. Furthermore, QFD is an iterative process. After initially scoring each R&T Challenge, panel members examined their results, assessed the justifications for each score for internal consistency and accuracy, and then adjusted some scores and justifications, as appropriate.

Once each panel completed the QFD process for its R&T Area, the steering committee reviewed the results and raised issues for the panels to reconsider to assure that the results were generally consistent when two panels had similar R&T Challenges. In the end, the panels and the steering committee concurred that (1) the Strategic Objectives were properly defined and weighted and (2) the Challenges were correctly scored and prioritized. Thus, although the steering committee reserved the right to change QFD scores without the concurrence of the panels, it did not find such action necessary.

The steering committee could have attempted to create a single integrated priority list of the R&T Challenges from all five R&T Areas. However, it was not practical for the committee to make extensive pairwise comparisons to assure that the scores for each R&T Challenge from each panel were consistent with the scores for dissimilar R&T Challenges from other panels. The steering committee also considered the value of having a single list of priorities and satisfied itself that (1) the results from each panel were generally consistent and well justified; (2) the high-priority R&T Challenges in each R&T Area were, indeed, high-priority items that should be included in NASA s aeronautics R&T program; and (3) the ultimate purpose of prioritizing R&T Challenges is presumably to determine which Challenges will be funded, and that determination will depend upon budgetary factors that were beyond the scope of this study (see Appendix G).

Given the above considerations, instead of creating an integrated, prioritized list of R&T Challenges from all five panels, the steering committee decided that the best use of the limited time and resources available to complete the study would be to identify Common Themes and formulate overall findings and recommendations (see Chapters 4 and 5). Given this situation, readers are cautioned against comparing the national and NASA priority scores for R&T Challenges from *different* panels to determine which is more important. The steering committee firmly believes that NASA should support research in all five R&T Areas, and the priorities identified in this report can be relied on to guide research planning within each of those areas.

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3

Research and Technology Challenges

The highest priority R&T Challenges for each R&T Area are listed and discussed below. The section for each Area includes a table showing the results of the quality function deployment (QFD) evaluation of R&T Challenges for that area. Each section also discusses general characteristics of high- and low-priority challenges in the relevant Area, R&T Thrusts that encompass multiple Challenges from a given area, and specific Challenges that rank high in national priority, but low in NASA priority. More detailed information for each Challenge appears in Appendixes A to E.

AERODYNAMICS AND AEROACOUSTICS

Introduction

Aerodynamics and aeroacoustics research is required to support development of advanced aeronautical systems. The scope of this R&T Area includes a wide range of fundamental fluid dynamic research ranging from low-speed, low-Reynolds-number flows to hypersonic, chemically reacting flows to aerodynamic issues associated with flight in alternative atmospheres. It does not include aerodynamic issues associated with ground transportation systems or fluid dynamic issues associated with hydrodynamic flows or the space environment.

The QFD process described in Chapter 2 was used to prioritize 19 R&T Challenges related to aerodynamics and aeroacoustics. Table 3-1 and Figure 3-1 show the results. The text that follows describes the 11 R&T Challenges that ranked highest in terms of NASA priority, the general characteristics of high- and low-priority Challenges, and the R&T Thrusts in this Area.[1] Further details on all the challenges, including the rationale for scoring, are found in Appendix A.

In terms of national priority, challenges A1, A2, A3, A6, and A7b all fall within a narrow range. Taking account of the weighting factors and scores, and noting that small changes in many of those elements can produce important changes in the final order, it should be concluded that these challenges are of roughly equal importance.

Top 11 R&T Challenges

A1 Integrated system performance through novel propulsion–airframe integration

Research into improved techniques for propulsion–airframe integration is required to enable greater aircraft flexibility and improve performance, especially as aircraft speeds increase. Improvements in the accuracy of predictions for three-dimensional (3-D) steady and unsteady interactions between external and internal aerodynamics and aeroacoustics would enable the design of advanced aeronautical systems, especially with systems of unconventional design. These interactions include the effects of steady and dynamic distortion on engine operations and the effects of hot, reacting exhaust flows on vehicle aerodynamics. These interactions are particularly important in the design of vertical and short takeoff and landing (V/STOL), extremely short takeoff and landing (ESTOL), supersonic, and hypersonic airplanes.[2]

[1]This chapter describes the top 10 R&T Challenges in each Area, except for the aeronautics and aeroacoustics Area. As shown in Figure 3-1, the NASA priority scores for Challenges A4a through A11 were relatively close, and there was a large difference in the scores for A11 and A12, so in this Area, unlike the remaining four, the top 11 R&T Challenges are described in the aeronautics and aeroacoustics Area.

[2]VTOL airplanes can take off and land vertically. This includes tiltrotors, the AV-8 Harrier, and the Joint Strike Fighter (JSF), for example. VTOL airplanes do not routinely take off or land vertically because of the range-payload penalty associated with the weight limitations of purely vertical operations. Rather, they use any available field length to develop some forward motion and wing lift during takeoff to increase the useful load (fuel plus payload). They tend to land vertically only at the end of the mission, when they are lighter, after burning fuel and/or dropping weapons.

STOL airplanes use high-lift systems to take off in less distance than

TABLE 3-1 Prioritization of R&T Challenges for Area A: Aerodynamics and Aerocoustics

		Strategic Objective							Why NASA?					
R&T Challenge	Weight	Capacity	Safety and Reliability	Efficiency and Performance	Energy and the Environment	Synergies with Security	Support to Space	National Priority	Supporting Infrastructure	Mission Alignment	Lack of Alternative Sponsors	Appropriate Level of Risk	Why NASA Composite Score	NASA Priority Score
		5	5	3	3	1	1		$^{1}/_{4}$ each					
A1	Integrated system performance through novel propulsion–airframe integration	9	3	9	9	9	9	**132**	3	9	3	9	**6.0**	**792**
A2	Aerodynamic performance improvement through transition, boundary layer, and separation control	9	3	9	9	3	3	**120**	3	9	3	9	**6.0**	**720**
A3	Novel aerodynamic configurations that enable high performance and/or flexible multimission aircraft	9	3	9	9	3	1	**118**	3	9	3	9	**6.0**	**708**
A4a	Aerodynamic designs and flow control schemes to reduce aircraft and rotor noise	9	1	3	9	3	1	**90**	3	9	3	9	**6.0**	**540**
A4b	Accuracy of prediction of aerodynamic performance of complex 3-D configurations, including improved boundary layer transition and turbulence models and associated design tools	3	3	9	3	3	3	**72**	9	9	3	9	**7.5**	**540**
A6	Aerodynamics robust to atmospheric disturbances and adverse weather conditions, including icing	9	9	3	1	9	1	**112**	3	9	3	3	**4.5**	**504**
A7a	Aerodynamic configurations to leverage advantages of formation flying	3	1	9	9	3	1	**78**	3	9	9	3	**6.0**	**468**
A7b	Accuracy of wake vortex prediction, and vortex detection and mitigation techniques	9	9	3	1	1	1	**104**	3	9	3	3	**4.5**	**468**
A9	Aerodynamic performance for V/STOL and ESTOL, including adequate control power	9	3	3	1	3	1	**76**	3	9	3	9	**6.0**	**456**
A10	Techniques for reducing/mitigating sonic boom through novel aircraft shaping	3	1	3	9	3	1	**60**	9	9	3	9	**7.5**	**450**
A11	Robust and efficient multidisciplinary design tools	3	3	9	9	3	3	**90**	3	9	3	3	**4.5**	**405**
A12	Accurate predictions of thermal balance and techniques for the reduction of heat transfer to hypersonic vehicles	1	1	3	1	9	9	**40**	9	9	3	9	**7.5**	**300**
A13	Low-speed takeoff and landing flight characteristics for access-to-space vehicles	1	3	1	1	3	9	**38**	3	9	9	9	**7.5**	**285**
A14	Efficient control authority of advanced configurations to permit robust operations at hypersonic speeds and for access-to-space vehicles	1	1	3	1	9	9	**40**	3	9	3	9	**6.0**	**240**
A15	Decelerator technology for planetary entry	1	1	1	1	3	9	**28**	3	9	9	9	**7.5**	**210**
A16	Low-Reynolds-number and unsteady aerodynamics for small UAVs	1	1	3	1	9	3	**34**	3	9	3	9	**6.0**	**204**
A17	Low-drag airship designs to enable long-duration stratospheric flight	1	3	1	3	9	1	**42**	3	3	3	9	**4.5**	**189**
A18	Prediction of communication capability through reentry trajectory and techniques to mitigate impact of communication blackouts	1	1	1	1	9	9	**34**	3	9	3	3	**4.5**	**153**
A19	Aircraft protective countermeasures based on a range of small deployed air vehicles	1	3	1	1	9	1	**36**	3	3	3	3	**3.0**	**108**

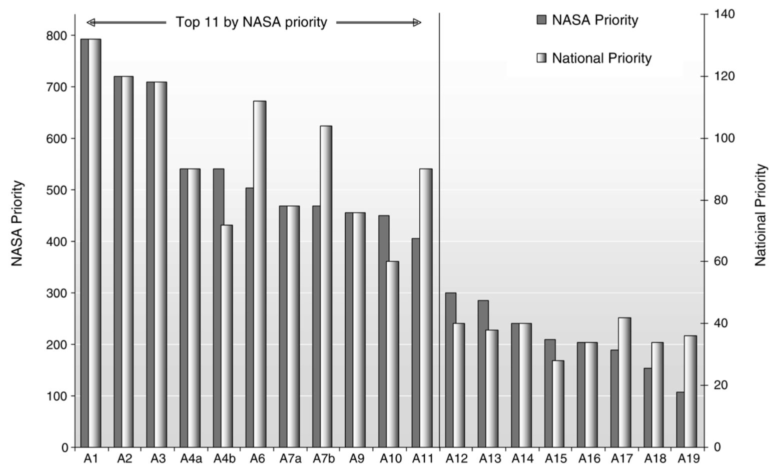

FIGURE 3-1 NASA and national priorities for Area A: aerodynamics and aeroacoustics.

Minimization of drag by propulsion–airframe integration will reduce fuel burn and CO_2 emissions.

A2 Aerodynamic performance improvement through transition, boundary layer, and separation control

Viscous drag at subsonic, supersonic, or hypersonic speeds may be reduced by controlling the onset of boundary layer transition using active control or passive 3-D design concepts. Direct reduction of skin friction drag is possible with extensive laminar flow, which can be achieved with a combination of vehicle shaping and flow control concepts. One example is natural laminar flow using reduced sweep and control of crossflow pressure gradients through shape optimization. A second example is boundary layer manipulation through suction, blowing, or distributed effectors. Related concepts may also be used to reduce separation at high lift and other conditions (e.g., buffet), which improves performance at high-lift conditions. In some conditions of flight, particularly at high lift, a turbulent boundary layer is needed. Active flow control techniques are emerging, including piezoelectric, voice-coil, dielectric barrier discharges, and surface electrical discharges. The potential advantages are clear, but implementation has been hampered by the lack of accurate and efficient methods for prediction (see Challenge A4b) and design and by the difficulty of conducting experiments that require high Reynolds numbers and are sensitive to disturbances such as free-stream turbulence and noise. Work on this Challenge should identify the most promising application domains, control approaches, and actuator concepts and develop efficient methods for design and experimental validation.

A3 Novel aerodynamic configurations that enable high performance and/or flexible multimission aircraft

Most classes of aircraft configuration have remained constant for many years (e.g., the tube and wing of a subsonic transport and the main rotor plus tail rotor of a helicopter). Novel aerodynamic configurations provide substantial opportunities for long-term breakthroughs in aircraft capabili-

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conventional aircraft (typically a few thousand feet). Very few STOL aircraft can safely take off on runways shorter than 3,000 ft and none on runways less than 2,000 feet. (This class does not include ultralight aircraft, kit planes, etc. that can operate out of short fields due to their small size but do not have high-lift systems.)

ESTOL airplanes would be able to safely take off on runways of 2,000 ft. They would have high-lift systems and thrust-to-weight ratios that are higher than conventional aircraft but not as high as VTOL aircraft. ESTOL aircraft have not yet been developed for commercial or military operations.

V/STOL refers to both VTOL and STOL airplanes that convert to fixed-wing flight after takeoff; it does not include helicopters.

ties. A number of innovative concepts have been proposed in the past and pursued to differing levels. Examples include the blended wing body, canard rotor wing, oblique flying wing, and strut-braced wing. A sustained research program should be promoted to develop novel aircraft configurations, including further development of existing concepts where appropriate, with emphasis on achieving breakthroughs related to the high-priority Strategic Objectives.

Other R&T Challenges would also contribute to enabling novel aerodynamic configurations. Advances in flight mechanics and propulsion–airframe integration (R&T Challenge A1) are required to make advanced concept airplanes viable and robust. Flow control (R&T Challenge A2) could significantly enhance the capability of novel configurations, since it could be assumed a priori in the design process rather than added as an improvement to an existing airplane. Research related to the Common Theme of physics-based analysis tools is needed to move beyond empirical design tools.[3] In addition, flight testing is a critical element of a successful research program in novel configurations.

A4a Aerodynamic designs and flow control schemes to reduce aircraft and rotor noise

Many of today s airports now limit operations because of the noise emitted to the surrounding community. Future passenger growth at many airports will be limited if the noise levels emitted by the newer aircraft are not reduced further, thus adversely affecting capacity. Off-loading the main runway of regional jets by using ESTOL aircraft and rotorcraft, thus reducing congestion for larger passenger aircraft on the main runway, will dramatically increase capacity by allowing more takeoffs and landings at existing airports without increasing demand for runway usage (NRC, 2003; FAA, 2000). However, it will only be possible if these ESTOL aircraft and rotorcraft are quiet. Aerodynamic noise research should be pursued to (1) improve understanding of the underlying flow physics, (2) develop novel technologies, and (3) create improved and validated acoustic prediction and design tools. This research should include a balance of physics modeling, tool development, and experiments. Important physical phenomena that require research include cavity flows, unsteady flow–solid surface interactions, flow separation, rotor dynamic stall, and wake vortex dynamics. Novel needs include quiet, high-lift devices; technologies to enable steep, quiet, slow-approach trajectories; technologies to reduce the strength of vortices shed from the rotor blades and/or vortex/blade position control; integrated advanced control schemes for active rotorcraft noise reduction; and technologies to reduce rotor response to vortex-induced disturbances. Physics-based source noise prediction methods and improved computational aeroacoustic tools are key requirements. Design tools are needed both at the technology level and at the aircraft system level, with particular attention to integrated solutions for aerodynamic and operational issues.

A4b Accuracy of prediction of aerodynamic performance of complex 3-D configurations, including improved boundary layer transition and turbulence models and associated design tools

The aerospace industry lacks computational analysis and design tools that can rapidly and accurately predict complex flow behavior driven by boundary layer transition, flow separation, novel configurations, off-design operations, and multidisciplinary interactions. To meet this need, physics-based design tools must be developed and systematically validated in representative environments. Ideally, these tools should have the following attributes:

- Adaptive and intelligent self-generating grids that are easily implemented using simple computer-aided design surface instructions, minimal boundary condition definition, and desktop operation.
- Seamless applicability over the continuum of fluid flows (speed regimes, phase, periodicity) and reference frames.
- Ability to accurately predict transitional and separated flows, validated through experimentation.
- Ability to fully describe the state of the fluid at any point in the solution domain, with useful information on the surfaces.
- Inverse design capability.

The benefit of technologies developed by this Challenge would be enhanced by parallel development of multidisciplinary design tools to address complex nonlinear interactions, and parameter uncertainties and models, while still being computationally efficient (see Challenge A11).

A6 Aerodynamics robust to atmospheric disturbances and adverse weather conditions, including icing

Adverse weather conditions, including storms and icing conditions, significantly reduce the capacity and reliability of the air transportation system. Adverse weather also degrades system safety. This issue is of importance to both civil and military aviation. Research is needed to improve the ability to predict and monitor environmental conditions and develop aerodynamic designs and techniques that are robust to adverse conditions.

At present, wind-shear warning systems are built into commercial aircraft, icing hazards are handled by regulatory constraints on flight operations, and prediction techniques are largely empirical. Low-cost techniques to mea-

[3]"Physics-based" refers to the general use of scientific principles in the place of empirical data. It includes the use of principles from chemistry, biology, material science, etc.

sure upstream environmental conditions should be developed. Examples of promising techniques include microwave, lidar, and laser-acoustic measurement techniques. Efforts to miniaturize and reduce the cost of the measurement equipment should be supported. Techniques to predict and mitigate the impact of adverse environmental conditions on the aircraft operation should be improved. Required improvements include the development of models to predict the impact of multiphase, nonequilibrium situations encountered under icing conditions; validation of icing prediction capabilities to enable a reduction in the high cost of aircraft and helicopter icing certification; and models for the complex-flow, time-dependent, 3-D interactions encountered during wind shear or ambient turbulence on the aircraft flowfield.

A7a Aerodynamic configurations to leverage advantages of formation flying

Formation flight is currently used by military airplanes for a variety of operational reasons, although rarely for drag reduction. Recent breakthroughs in accurate navigation and control make possible extended precision formation flight at cruise and permit exploitation of favorable interference for vortex drag reduction. Although this phenomenon is well known, the magnitude of the potential savings is not widely appreciated. Three airplanes flying in formation and designed to best exploit these effects could reduce vortex drag by more than 50 percent in cruise, a greater reduction than that obtainable by extensive laminar flow control on the wing. This would mean roughly a 20 percent reduction in total drag under identical operating conditions. However, with less induced drag the optimum altitude increases, reducing viscous drag as well. The net result is almost a 30 percent reduction in total drag. Unlike the tight formations required for military applications, drag savings are possible even with longitudinal separations of several miles (Spalart, 1998), reducing safety concerns associated with formation flight.

Initial NASA work on autonomous formation flight has identified some of the technology requirements for achieving these savings, but considerable research remains in both control methodology and aerodynamic design to take most advantage of the concept. Applications to cargo airplanes, rotorcraft, and even supersonic flight are possible but have not been studied extensively. Aerodynamic challenges include vortex location prediction, sensing and control, and wing design for efficient high-lift cruise. Suggested work in this area would result in improved methods for predicting wake vortex evolution; design tools for evaluation and optimization of multiple interacting airplanes; and experimental validation, including flight testing (which is especially important for evaluating real atmospheric effects). The aerodynamic aspects of formation flying are related to R&T Challenges D1 and E2.

A7b Accuracy of wake vortex prediction, and vortex detection and mitigation techniques

Wingtip vortices produced by airplanes present a danger to following aircraft, so airplane designs and techniques that mitigate the strength of these vortices, techniques to locate and determine their strength, and techniques to predict their propagation and decay are important factors in minimizing aircraft separation and enhancing safety.[4] (Since aircraft lift is intimately tied to the production of circulation, these vortices cannot be completely eliminated.) Currently, aircraft separation standards are set by conservative estimates of the wake vortex trajectory (generally a sinking trajectory, but also affected by local weather conditions) and decay rate. Techniques to measure the characteristics of upstream wake vortices include lidar and laser-acoustic techniques, but these technologies are currently expensive (limiting their use to larger aircraft) and are less reliable than desired.

Research into techniques to predict the formation, trajectory, and decay of vortices needs to be performed. This includes development and validation of numerical methods to accurately predict the trajectory and dissipation of vortices, integration of local weather prediction techniques into existing larger-scale weather models, demonstration of low-cost techniques for locating and measuring the strength of wake vortices for both ground-based and aircraft-based applications, and investigation of airplane designs that mitigate the strength of wake vortices.

A9 Aerodynamic performance for V/STOL and ESTOL, including adequate control power

The development of ESTOL regional jets able to operate from 2,000 ft runways and taxiways and to cruise in existing air traffic corridors will significantly reduce congestion problems on the main runways of hub airports. V/STOL aircraft will be able to operate from taxiways and other paved areas at major airports, further relieving congestion. In responding to natural disasters and carrying out military operations, low-cost VTOL tactical transports would be able to operate from short, austere landing fields near the focus of attention (e.g., the location of injured civilians or troops, battle areas, and landslides).

Development of an efficient high-lift system is not the most important enabling technology for ESTOL airplanes. Conventional aerodynamic control surfaces become ineffective at the low landing and takeoff speeds of ESTOL airplanes (on the order of 65 knots). The challenge is to generate the forces needed for pitch trim and to control the aircraft at these slow speeds. It is also important to develop a thrust vectoring and reversing nozzle technology that not only provides the required lift but can also be integrated into a low-

[4]The scope of this Challenge does not include and would not directly apply to helicopter blade wakes.

drag configuration. (ESTOL airplanes require much more thrust than conventional or STOL airplanes, but not as much as VTOL airplanes.) In addition, wing design and fuselage shaping are needed to reduce cruise drag in the transonic regime for ESTOL regional jets.

An important task for research related to rotorcraft and VTOL airplanes is to improve hovering and cruise efficiency. Reductions in downward forces in near-hovering flight dramatically improve the payload capability of tiltrotor and powered-lift aircraft. Active control of large separation regions on these aircraft through blowing, zero-mass effectors, and integrated mechanical devices are promising methods for reducing download. Active twist control of the rotor also allows the rotorcraft to be designed to better match the hover and cruise design conditions, thereby improving efficiency. Active control of separation regions and smart design guided by high-fidelity codes will decrease cruise drag and improve the performance of VTOL airplanes.

A10 Techniques for reducing/mitigating sonic boom through novel aircraft shaping

Safe, efficient, cost-effective, environmentally acceptable supersonic flight over land remains elusive nearly 60 years after airplanes broke the sound barrier. The principal remaining problems are sonic boom mitigation, public acceptance, and sustained supersonic flight performance. Today, federal regulations prohibit civil supersonic flight over land. If this regulatory barrier can be overcome, it will probably stimulate investment that would overcome the other barriers and help usher in a new era of time-critical air travel. Building on the recent in-flight validation of NASA s theory of shaped sonic boom persistence, a robust and comprehensive plan of research for technology maturation and tool development should be pursued to determine if practical supersonic airplanes can be developed whose sonic boom is acceptable to the public (Pawlowski et al., 2005). Such a plan should comprise public sonic boom acceptability determination; community exposure testing; aircraft shaping techniques that result in a low-amplitude, acceptable acoustic signature with minimal performance impact; critical propulsion-airframe integration technologies commensurate with low-boom design; aircraft and acoustic scaling methodologies; sensitivities to off-design conditions under a variety of atmospheric conditions; rapid and inverse computational design tools that address multiple design constraints; systematic validation through ground and flight tests; and metrics to assess progress and guide continuation according to plan. This Challenge is closely tied to Challenge B8.

A11 Robust and efficient multidisciplinary design tools

Multidisciplinary design tools are pervasive in aeronautics. More effective multidisciplinary tools would likely shorten the design cycle time for conventional aircraft and facilitate the discovery of new highly integrated aircraft designs with better performance than conventional designs. The development of physics-based models for this design environment is addressed in R&T Challenge A4b. This Challenge is associated with the research required to efficiently and effectively integrate multidisciplinary design tools of varying fidelity and numerical complexity into a seamless design environment. Research is also needed on automated techniques for handling and propagating parameter uncertainties throughout the design to allow development of robust aircraft designs.

High-Priority R&T Challenges and Their Associated Thrusts

Some of the high-priority R&T Challenges significantly impact multiple Strategic Objectives; others are high priority because NASA possesses unique capabilities to address them. In particular, R&T Challenges that significantly improve capacity or safety and reliability scored high due to the relevant weightings. The principal factors affecting an increase in capacity relate to expanding the operational capabilities near airports, expanding flight capabilities under adverse weather conditions, and enabling an expansion of operation from smaller airports. The expansion of operations near airports will require research into noise reduction and aircraft wake physics. Expansion of operations under adverse weather conditions will require research associated with techniques to monitor and then mitigate adverse environmental conditions, including icing, wind shear, and free-stream turbulence. Expansion of operations from smaller airports involves research on shortened takeoffs and landings and the associated noise reduction.

The development of improved physical models and design tools for aerodynamic and aeroacoustic phenomena and techniques aimed at understanding and providing the option of controlling these phenomena rank high in the R&T Challenge prioritization. Mastery of these Challenges will enable significant advances in the performance and operability of aircraft through development of improved and possibly revolutionary designs and reduction of design margins associated with uncertainties.

The following four R&T Thrusts describe threads of commonality among the R&T Challenges within the aerodynamics and aeroacoustics Area.

Improved understanding and control of the fundamental physics of aerodynamic and aeroacoustic phenomena

Complex fluid dynamic processes often present barriers to improved aircraft performance, so a better understanding of these phenomena is required. These processes can occur across significant spatial and temporal scales and involve interactions with processes that come under the purview of other disciplines. With a deeper knowledge of the fundamental physical phenomena, effective techniques will likely evolve to control these processes, enabling improved aircraft performance.

Accurate and robust multidisciplinary design tools

Aeronautics is fundamentally multidisciplinary, so many aspects of aerodynamics and aeroacoustics are impacted by cross-discipline factors. Multidisciplinary aerodynamic and aeroacoustic design tools are needed that are accurate and robust yet cost-effective in terms of computing time and computational resources.

Sensing and responding to the external environment

Development of aircraft systems that respond dynamically to the local environment could significantly improve capacity and safety. With measurement techniques to sense the local environment ahead of an aircraft and allow it to respond accordingly, aircraft spacing can be reduced and operations in adverse weather can be expanded, with no degradation of safety.

Revolutionary aerodynamic configurations

Even though the basic design of civil aircraft has remained remarkably stable for many decades, it is not clear that the configuration has already been optimized. The steering committee believes that improved understanding and control of fluid dynamic phenomena will result in novel aircraft designs offering revolutionary advances in performance and operability in all mission areas.

Low-Priority R&T Challenges

No attempt was made to compile and assess all possible aerodynamic and aeroacoustic issues. All of the Challenges described above are relevant to fundamental aeronautics of civil aircraft. The aerodynamic Challenges that ranked low in the prioritization were largely research areas that support national or homeland security or the NASA space mission but minimally impact Strategic Objectives directly related to the performance of the air transportation system. Examples of these Challenges include hypersonic vehicle technologies, small UAVs, and stratospheric airships. These Challenges could play a vital role in NASA s space exploration mission and in matters of national and homeland security; however, they ranked low in terms of both national and NASA priority for this report, where the focus is on civil aeronautics.

Hypersonic technologies appear in Challenges throughout the prioritization list. Challenges associated with the development of a more complete understanding of hypersonic issues, such as transition, turbulence, and separation phenomena and the development of techniques to control these phenomena, are included in high-priority R&T Challenges that encompass multiple speed regimes. Challenges specific to hypersonic vehicles, such as low-speed handling characteristics, are rated much lower.

PROPULSION AND POWER

Introduction

This section describes key R&T Challenges and Thrusts associated with aircraft propulsion and electrical power generation that should be addressed via basic and applied research to advance national civil aeronautics capabilities. These advances will permit the U.S. aeronautics enterprise to bring highly competitive products to market and improve the national capacity to move people and goods quickly and affordably with minimal energy usage and environmental impact.

Historically, paradigm shifts in propulsion capability have enabled significant advances in aircraft performance. The replacement of water-cooled piston engines with radial, air-cooled engines enabled the great airframe advances of the first half of the 20th century, while those in the second half were greatly expedited by the gas turbine engine. The gas turbine will very likely continue to be the dominant means of propulsion for both civilian and military aircraft for the next half century. With oil prices at historic highs and increasingly stringent noise and emissions regulations, gas turbine designers face formidable obstacles to create more fuel efficient, cleaner, and quieter engines. Opportunities abound for significant advances, with current gas turbine performance still well below theoretical limits. For example, improvements in overall efficiency and, concomitantly, fuel economy, of more than 30 percent appear attainable (Koff, 2004) but will only occur with significant advances in high-temperature materials and rotating machinery aerodynamics. With advances in information technology, sensor miniaturization, and modeling, intelligent engines capable of self-diagnosis and adaptation, similar to those in the automotive realm, are in the offing. Advances in information technology are also driving electrical power demands for both flight systems and passenger needs—that is, entertainment and productivity. The desire for rapid yet affordable transcontinental and intercontinental travel will continue to motivate research into supersonic flight engines; it is difficult to imagine commercial aviation being restricted to subsonic flight regimes 50 years from now. Airbreathing engine technology also has the potential to contribute significantly to the development of reusable higher payload fraction, access-to-space vehicles. Technical progress will be greatly expedited by the use of validated, physics-based computational simulation tools, which will permit designers to optimize designs and greatly minimize the number of design cycles typical of empirical design-build-test-redesign approaches.

The QFD process described in Chapter 2 was used to prioritize 16 R&T Challenges related to the Area of propulsion and power. Table 3-2 and Figure 3-2 show the results. The text that follows describes the 10 R&T Challenges that ranked highest in terms of NASA priority, the general characteristics of high- and low-priority Challenges, and the R&T Thrusts in this Area. Further details on all Challenges, including the rationale for scoring, are found in Appendix B.

Top 10 R&T Challenges

B1a Quiet propulsion systems

Public concerns over the environmental impact of aircraft and airport operations—primarily noise and emissions—have prompted increasingly strict legal and regulatory requirements, which can severely constrain the ability of civil aviation to meet national and global needs for mobility, increased market access, and sustained economic growth. Aircraft noise concerns include takeoff and landing noise; taxi and engine run-up noise; flyovers at cruise altitude over very quiet areas; and sonic booms associated with supersonic flight.

Figure 3-3 shows how the impact of aviation noise on people living around airports has declined in the United States. It contrasts the growth of air travel with the reduction in the number of people exposed to 65-decibel (dB) day-night average sound level (DNL), which is what the federal government has defined as the "significant noise level." Since 1975, the number of persons exposed to significant noise levels has greatly declined, with the transition of commercial aircraft to quieter models even as air travel has grown dramatically. The availability of low-noise technologies, such as high-bypass-ratio engines, contributed significantly to this transition. Assuming the industry s continued recovery, and given the goal of doubling capacity over the next 10 to 35 years, the dramatic improvements in noise exposure in the last two decades are unlikely to persist. The environmental impact of aircraft noise is projected to remain roughly constant in the United States for the next several years and then increase as air travel growth outpaces expected technological and operational advancements (Waitz et al., 2004). Furthermore, the public currently reports considerable annoyance even when DNLs are below 65 dB. Regulatory actions to limit or reduce noise exposure will likely lead to even more stringent limits.

Future abatement efforts may need to reduce allowable noise levels to as low as 55 dB DNL in both the United States (NASA, 2003) and Europe (ACARE, 2001). Meeting future noise targets will be extremely challenging and will require continued fundamental research in noise phenomena and advanced propulsion technologies. The development of validated, physics-based noise prediction tools by NASA will greatly aid the development of quieter engines. Research is needed to reduce the noise of engine systems, including fan noise, jet noise, and core noise. Research should also encompass systems analysis; advanced concepts, such as adaptable chevrons; the community impact of aircraft noise; and improved metrics to quantify and mitigate these impacts.

B1b Ultraclean gas turbine combustors to reduce gaseous and particulate emissions in all flight segments

Emissions from aircraft constrain the growth of aviation due to their environmental impacts and potential human health consequences. For example, airports located in air quality nonattainment or maintenance areas increasingly find that air emissions add to the complexity, length, and uncertainty of the environmental review and approval of expansion projects (Akin et al., 2003).

Key pollutants of concern include oxides of nitrogen and sulfur (NO_x and SO_x), carbon monoxide (CO), unburned hydrocarbons (UHCs), hazardous air pollutants, and particulate matter (PM). In addition, emissions of CO_2 and water vapor (H_2O) in the upper troposphere and stratosphere are of concern because of their potential impact on Earth s climate (IPCC, 1999). Both CO_2 and H_2O are inherent combustion products of hydrocarbon fuels, and their emissions can only be reduced through improvements in overall cycle efficiency (see R&T Challenge B4)—or a change in fuels. Emissions of NO_x, CO, UHC, and PM from the combustor can be reduced through the development of ultraclean combustion approaches, a critical step to mitigate the environmental impacts of aviation.

Low NO_x emissions can be achieved with both rich- and lean-burning combustor designs. Lean combustion concepts have received substantial market penetration through their widespread implementation in land-based gas turbine applications over the last two decades. The key technical issues associated with these combustors concern unsteady combustion phenomena, including combustion instability, flame blow-off, flashback, and autoignition. Although combustors run lean overall, the majority of commercial aircraft engines run rich in the front end. The key issues associated with them are PM emissions and quench zone mixing (Lefebvre, 1999).

B3 Intelligent engines and mechanical power systems capable of self-diagnosis and reconfiguration between shop visits

In the future, advances in sensing, control, and information technology will lead to engines that are more sophisticated and more intelligent. Research thrusts should investigate how more intelligent systems can (1) improve engine health diagnostics and remedial actions in flight, (2) optimize the mission, and (3) use flight data to improve maintenance on the ground. For current engines, the focus will be very much on diagnostics. Better physics-based modeling will be essential. Development of better computational fluid dynamics (CFD) tools, life-prediction tools, and steady-state and dynamic performance checks will be keys to success. Reducing in-flight shutdowns by a factor of 3 and unscheduled engines removals and delays and cancellations by a factor of 5 should be achievable and would reduce maintenance costs by 50 percent. Requirements include (1) smaller sensors with better response and higher operating temperatures and (2) better materials with narrower property tolerances. This should increase disk and airfoil life by 50 percent.

Intelligent engine development will include active control of many engine components: combustor control to permit operation with leaner burners, leading to lower NO_x emissions; compressor active stall control to allow operation at higher pressure ratios, leading to higher fuel efficiency; and closed-loop clearance control to increase turbine efficiencies and extend on-wing life by 3 years.

B4 Improved propulsion system fuel economy

The fuel economy of gas turbine propulsion systems is a function of engine efficiency, propulsion-induced drag, and propulsion weight. Overall engine efficiency is the product of the efficiency of creating hot, high-pressure gases (thermal or cycle efficiency), the efficiency of transferring energy from the hot high-pressure gases to a more desirable form (transfer efficiency), and the efficiency of creating thrust from the engine fan and core flows (propulsion efficiency). The thermal efficiency for a gas turbine (Brayton cycle) is primarily a function of overall engine pressure ratio. That is, as long as the turbine can tolerate the inlet temperature corresponding to a given pressure ratio, the overall pressure ratio sets the efficiency of the cycle. Figure 3-4 illustrates very clearly that state-of-the-art gas turbines have not reached the theoretical limits of thermal efficiency. The technologies identified in the figure have the potential to improve the thermal efficiency of gas turbines, to significantly increase fuel economy, and to decrease the environmental impact of the air transportation system.

Transfer efficiency is determined by the component efficiencies of the fan and low-pressure turbine and the losses of the shaft bearings. High-efficiency, low-pressure turbines need high rotor speeds, but highly efficient fans require low rotor speeds. Therefore, engines with high transfer efficiency must have reduction gearboxes or other technologies that permit different rotor speeds for the fan and low-pressure turbine.

Propulsion efficiency is a function of the difference between the velocity of engine exhaust and the forward velocity of the aircraft. Increasing the mass flow of air through the system at slower speed improves propulsion efficiency and decreases noise. However, this increases the diameter of the engine, which increases friction and flow blockage. Since larger engines will also be heavier, the use of composites or other lightweight materials for construction of the large structural pieces of the turbofan will also be necessary.

As shown in Figure 3-4, improving thermal efficiency by 15 percent requires advances in several technologies: 3D aerodynamics, active flow control, cooled cooling air and a thermal management system, multiwalled cooling, and ceramic matrix composites (CMCs) and intermetallics. Over the long term, advances in all three efficiencies (thermal, transfer, and propulsion) should be able to improve fuel economy by 30 percent relative to the GE-90 for large commercial engines and 30 percent relative to T700/CT7 for small engines.

B5 Propulsion systems for short takeoff and vertical lift

The utilization of V/STOL airplanes and increased use of helicopters could greatly increase the capacity of civil aviation by allowing more takeoffs and landings at existing airports without increasing demand for runway usage (NRC, 2003). V/STOL airplanes include tilt-wing aircraft, tilt-rotor aircraft, vertical-lift fan aircraft, and blown-wing aircraft. Currently, the fuel economy of V/STOL propulsion systems is not on par with that of fixed-wing commercial airplanes. Propulsion systems for all new aircraft must also demonstrate extremely high levels of reliability. Propulsion systems for V/STOL aircraft are in an early state of development or do not exist for civil aircraft. In addition, engine-out strategies need to be developed and verified for certification.

This Challenge should support development of V/STOL and helicopter propulsion systems with fuel economy comparable to future small commercial aircraft—namely, 20 percent better than the CT7 family of engines that are currently in production for small conventional aircraft. Many of the same technologies that apply to large and small engines for conventional aircraft also apply to V/STOL propulsions systems. However, additional technologies such as high-efficiency, angled gearboxes; high-efficiency reduction gearboxes; large-bleed systems; thrust vectoring systems; noise reduction both inside and outside the aircraft; fan-tip-driven turbines; and high-power clutch systems will be required to put V/STOL airplanes into affordable, large-scale commercial service with minimal environmental impact.

There are three major technology efforts to be undertaken in support of V/STOL airplanes for civil aviation. The first and most important is to demonstrate an engine sized for most helicopters or for UAVs (roughly 3,000-shaft horsepower) that meets the fuel economy goals. The important characteristics of this demonstration engine are to achieve overall pressure ratios of 25:1 or 30:1 and turbine inlet temperatures of 2800°F. This will require some combination of the following technologies: (1) new compressor disk materials, (2) greatly improved turbine cooling configurations, (3) new turbine blade alloys and coatings, (4) component aerodynamics designed with the latest computational models, and (5) highly effective, low-pressure-drop dirt separation. Such an engine would benefit helicopters as well.

Second, the powertrain system of most V/STOL airplanes (as well as helicopters) will consist of shafting with speed reduction gearboxes, angled gearboxes, and perhaps

TABLE 3-2 Prioritization of R&T Challenges for Area B: Propulsion and Power

R&T Challenge		Capacity	Safety and Reliability	Efficiency and Performance	Energy and the Environment	Synergies with Security	Support to Space	National Priority	Supporting Infrastructure	Mission Alignment	Lack of Alternative Sponsors	Appropriate Level of Risk	Why NASA Composite Score	NASA Priority Score
		Strategic Objective							Why NASA?					
	Weight	5		3		1			$^{1}/_{4}$ each					
B1a	Quiet propulsion systems	9	1	3	9	3	1	**90**	3	9	3	9	**6.0**	**540**
B1b	Ultraclean gas turbine combustors to reduce gaseous and particulate emissions in all flight segments	9	1	3	9	3	1	**90**	3	9	3	9	**6.0**	**540**
B3	Intelligent engines and mechanical power systems capable of self-diagnosis and reconfiguration between shop visits	3	9	3	3	3	1	**82**	3	9	3	9	**6.0**	**492**
B4	Improved propulsion system fuel economy	3	1	9	9	3	1	**78**	3	9	3	9	**6.0**	**468**
B5	Propulsion systems for short takeoff and vertical lift	9	1	3	3	3	1	**72**	3	9	3	9	**6.0**	**432**
B6a	Variable-cycle engines to expand the operating envelope	3	1	9	3	3	9	**68**	3	9	3	9	**6.0**	**408**
B6b	Integrated power and thermal management systems	3	1	9	3	3	9	**68**	3	9	3	9	**6.0**	**408**
B8	Propulsion systems for supersonic flight	3	1	3	1	9	9	**50**	9	9	3	9	**7.5**	**375**
B9	High-reliability, high-performance, and high-power-density aircraft electric power systems	1	3	9	3	3	3	**62**	1	9	3	9	**5.5**	**341**
B10	Combined-cycle hypersonic propulsion systems with mode transition	1	1	3	1	9	9	**40**	9	9	3	9	**7.5**	**300**
B11	Alternative fuels and additives for propulsion that could broaden fuel sources and/or lessen environmental impact	3	1	3	9	3	1	**60**	3	3	3	9	**4.5**	**270**
B12	Hypersonic hydrocarbon-fueled scramjet	1	1	3	1	9	9	**40**	9	3	3	9	**6.0**	**240**
B13	Improved propulsion system tolerance to weather, inlet distortion, wake ingestion, bird strike, and foreign object damage	3	9	3	1	3	1	**76**	3	3	3	3	**3.0**	**228**
B14	Propulsion approaches employing specific planetary atmospheres in thrust-producing chemical reactions	1	1	1	1	1	9	**26**	3	9	9	9	**7.5**	**195**
B15	Environmentally benign propulsion systems, structural components, and chemicals	1	1	1	9	3	1	**44**	3	3	3	3	**3.0**	**132**
B16	Reduced engine manufacturing and maintenance costs	3	3	3	3	3	1	**52**	3	1	1	3	**2.0**	**104**

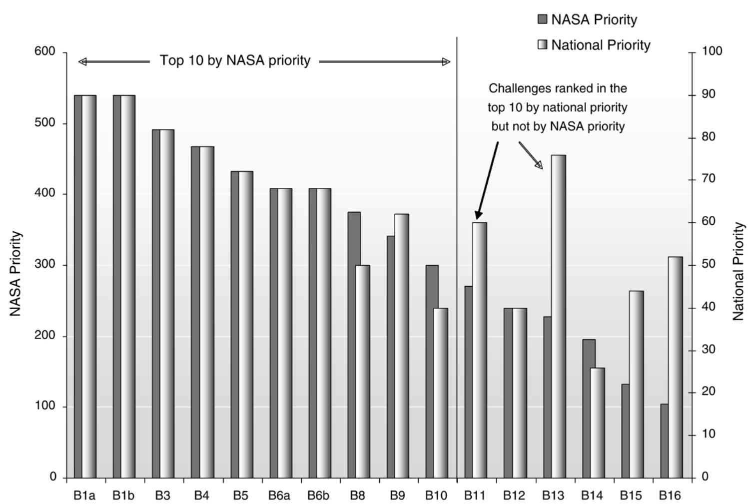

FIGURE 3-2 NASA and national priorities for Area B: propulsion and power.

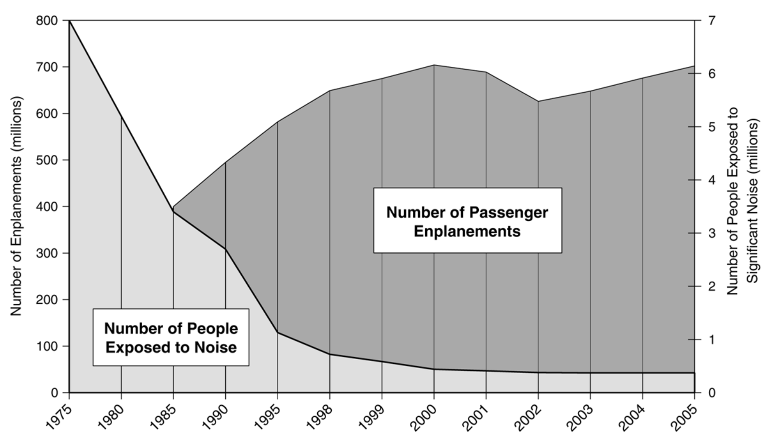

FIGURE 3-3 Actual and predicted exposure to significant noise (65-dB day-night average sound level) and enplanement trends for the United States, 1975-2005. SOURCE: C. Burleson, FAA, "Aviation environmental challenges," Presentation to Panel B, December 13, 2005.

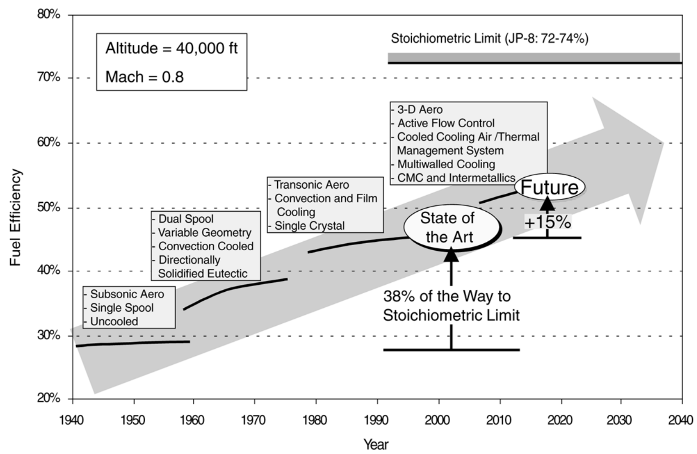

FIGURE 3-4 Considerable gas turbine fuel efficiency improvements are still possible. SOURCE: J. Stricker, Air Force Research Laboratory, Private communication to panel member D. Crow, February 2006.

clutch systems. The technology goal is to demonstrate highly reliable gearboxes with transfer efficiencies of about 99.8 percent and a power-to-weight ratio of 50 hp per pound. Reliable clutch operation would enable many new types of V/STOL aircraft.

Thirdly, engine-assisted wing lift, such as the blown wing, offers the simplest, most energy efficient short takeoff. Wing aerodynamics need to be developed, and the bleed or suction locations and quantities required need to be demonstrated for blown-wing V/STOL airplanes.

B6a Variable-cycle engines to expand the operating envelope

Variable-cycle engines have two or three flow paths through the engine, variable vanes, and variable exhaust nozzles, all of which allow them to vary engine bypass ratios and pressure ratios. They can improve the performance of both military and civil aircraft in many flight regimes by changing the bypass ratio and pressure ratio as a function of speed, altitude, and mission requirements. For the long-range Joint Strike Fighter (JSF), this should permit a twofold increase in rapid response radius, an eightfold increase in loiter capability, and a 30 percent reduction in gross weight. For a JSF follow-on aircraft, a 25 percent increase in lift and a 10-25 percent increase in range, depending on the mission, appear possible.

Variable-cycle engines have the potential to increase subsonic engine fuel economy. They also appear attractive for a supersonic commercial aircraft that has to accommodate stringent takeoff noise requirements and still achieve reasonable performance at supersonic speeds. For access to space, variable-cycle engines could provide a large reduction in payload costs as well as marked safety improvements.

This Challenge requires the development of numerous technologies: integrated thermal management approaches; reliable air-to-fuel heat exchangers; low-pressure-drop air-to-air heat exchangers; improved JP-8 heat sink capability; CMC technologies and associated life-prediction tools for operation above 2400°F; complex shape fabrication; high-speed bearings; improved turbine cooling; better engine health predictions; probabilistic life analysis; in-flight data analysis; low-emission, high-temperature combustors; variable-geometry fan systems; and improved airframe-engine integration. This Challenge would benefit from the development of intelligent engines (Challenge B3).

B6b Integrated power and thermal management systems

Efficiency can be enhanced by integrating and optimizing, at the vehicle level, the traditionally severable airframe power and thermal management systems. "Integration" refers to physical, functional, and requirements integration of key propulsion and power system components, by combining them into fewer, multifunctional units all tied together in a more-electric architecture (see Challenge B9). Key components and functions include engine starting; electrical power generation, power conditioning, and routing; air cycle environmental control; avionics, fuel, and oil cooling; ventilation; flight control actuation; and overall vehicle and propulsion system thermal management, especially waste heat recovery and/or rejection. For example, engine start, auxiliary power, and environmental control systems may be combined into an airframe-mounted integrated power package that is physically coupled to the engine through power extraction and waste heat recovery. In this integrated approach, flight control systems are likely to be driven by electric or electrohydrostatic actuators, and thermal management is addressed in a seamless, system-level fashion. At the propulsion system level, electric power must be generated and integrated with airframe needs in the most efficient manner. This may be by a generator mounted on the shaft of the low-pressure turbine or, eventually, by fuel-cell-driven generators distributed within the airframe.

Today s modeling tools are derived from legacy approaches in which numerous component suppliers individually design, develop, and validate their product based on component-level requirements and specifications. New modeling and simulation infrastructures are necessary to use modeling tools in a system-level design framework, accommodating multiple platforms across multiple sites. A robust modeling framework is necessary to justify the system-level benefit of a given integrated component that may weigh or cost more than a traditional component or have different or enhanced functionality.

B8 Propulsion systems for supersonic flight

Commercially viable supersonic propulsion remains an elusive goal. Key issues include system performance and efficiency, the current ban on civil supersonic flight over the continental United States (14 CFR 91 ¶817), and Stage 4 noise standards.

Particularly for supersonic flight, propulsion systems development needs to be integrated with the design of the rest of the aircraft in a multidisciplinary effort to find an optimal trade-off between performance, efficiency, noise, emissions, and thermal management. Engine–airframe integration becomes more critical as the flight speed increases. This Challenge requires validated physics-based numerical simulation codes for component-level analysis and the improvement of multidisciplinary, system-level design tools for vehicle analysis.

Gas turbine research topics of interest include

- Variable-cycle engines optimized for both subsonic and supersonic flight with low specific fuel consumption, high thrust-to-weight ratios (T/Ws), and low noise.
- Lightweight, low-noise, efficient inlets and nozzles that also reduce wave drag and help to shape the sonic boom efficiently.
- Integrated airframe and propulsion controls to actively reduce vibration mode interactions between the engine and the plane (NIA, 2005).
- Noise and emissions data to validate models for sonic boom signature and determine its effect on humans (psychoacoustics), to assess the interaction of combustion products with ozone, and to help establish or confirm noise and emissions regulations.
- Electric actuation systems to eliminate the need for high-temperature hydraulic actuation systems.
- Active flow control to improve engine efficiency, reduce noise, and enable different airframe–propulsion integration concepts.
- Combustion process physics: modeling and experimental validation of injection, mixing, ignition, finite-rate kinetics, turbulence–chemistry interactions, and combustion instability to improve efficiency and life.
- Advanced materials and coatings (including high-temperature alloys for compressor and turbine disks) that meet requirements for operating temperature, service life, strength, and propulsion system noise.
- Alternative engine cycles for supersonic flight that might replace or enhance traditional gas turbines.

Many of these technologies are discussed in other R&T Challenges; much of the research proposed for subsonic engines will build a foundation for supersonic flight.

B9 High-reliability, high-performance, and high-power-density aircraft electric power systems

Future aircraft power systems must be able to meet the demands of more-electric aircraft (MEA). Future aircraft will progressively replace more and more mechanical and hydraulic systems with electrical systems, and electrical loads imposed by conventional systems will also continue to grow, to improve performance, convenience, and reliability. The higher power requirements of conventional loads are being driven by advances in avionics as well as by passenger entertainment and productivity needs. For example, the electric power demand on Boeing s 787 is nearly 1 MW, which is double that of the Boeing 777 and many times that of the first U.S.-built commercial jet, the Boeing 707 (Ames, 2005). The growth of new MEA loads is being driven by advances in the capabilities of electric actuators and controls, and it is being enabled by the development of more flexible and reliable aircraft generators. This Challenge can be met by improving key components and system-level technologies:

- Tenfold increase in power density for electric generators and motors suitable for aircraft use.

- Fivefold increase in energy and power density of suitable batteries and hybrid storage systems (e.g., the battery–ultracapacitor).
- An order of magnitude lighter optimized power system architectures (including, for example, a DC power bus, remotely controlled loads, and a wireless system control).
- Intelligent power management and distribution (PMAD) using advanced system models and wireless sensors or sensorless control technologies for graceful degradation and failsafe operation.
- Advanced analysis and simulation tools for multiconverter power systems that can predict new modes of system dynamics and instability.

B10 Combined-cycle hypersonic propulsion systems with mode transition

The primary NASA hypersonics mission is for access to space in support of the Space Exploration Initiative and in placing and maintaining scientific payloads in low Earth orbit. A two-stage-to-orbit (TSTO) vehicle using a hydrogen-fueled, airbreathing first stage and a hydrogen-fueled rocket second stage could double the payload fraction to low Earth orbit relative to a two-stage, hydrogen-fueled rocket.[5] This would greatly reduce the cost of putting a payload into orbit. In addition, airbreathing hypersonic vehicles offer airplanelike operations, with increased safety and efficiency, more robust operation, and greater mission flexibility than rockets. A secondary mission for NASA hypersonics is to provide synergy with DoD programs in the development of missiles for time-critical targets; global strike and rapid resupply aircraft; and routine, on-demand access to space.

One combined-cycle hypersonic propulsion system under study for access to space is a turbine-based combined-cycle (TBCC) system. In order to design complex, combined-cycle hypersonic propulsion systems, experimentally validated, physics-based tools must be developed and refined because steady, full-enthalpy, clean air conditions cannot be reproduced in hypersonic ground test facilities. Experiments must be conducted on unit problems (e.g., jet injection into a supersonic stream) that contain the relevant flow physics but are amenable to simulation. Facility upgrades, such as for long-duration, high-temperature testing of engine materials and structures, should be completed in order to conduct the unit experiments under near-realistic flight conditions. Advanced diagnostics must be developed and used to obtain detailed databases in unit-problem experiments for complete validation of the computational tools, which can then be used for the vehicle design. Multiple-point validations are needed to verify that the tools produce results that can be extrapolated to conditions not available on the ground. Ultimately, flight testing must be conducted in order to obtain results under realistic operating conditions. Experiments should be flown on low-cost, suborbital rockets instead of expensive flight vehicles.

[5]P. Buckley, AFRL, "Payload mass fraction vs. staging velocity for TSTO vehicles to 51.7° orbit," Presentation to the DoD Technology Area Review and Assessment on March 29, 2004.

High-Priority R&T Challenges and Their Associated Thrusts

The rationale for the assignment of scores for each R&T Challenge is provided in Appendix B. In this section, the rationale for scoring will be discussed more generally. Table 3-2 shows that the top 10 R&T Challenges were all very relevant to NASA s mission, while those below the top 10 were less well aligned (with the exception of extraterrestrial planetary propulsion, which is clearly a NASA mission). In general, NASA has considerable infrastructure to support all the Challenges, with the exception of electric power systems, and NASA is particularly well equipped to conduct supersonic and hypersonic R&T. Other than propulsion in the atmospheres of extraterrestrial planets, industry, DoD, or, in a few cases, some other government agency will support R&T relevant to the high-priority Challenges. DoD, for example, has historically been a very strong supporter of V/STOL research. However, in the procurement-driven environment in which industry and the DoD live, time pressures often preclude achieving fundamental understanding, and empiricism must be resorted to when problems arise. Even though NASA may not be the only sponsor for some R&T, it can distinguish its research support by developing a fundamental understanding of phenomena, a strong commitment to physics-based modeling, and extensive validation of those models. All 10 high-priority Challenges entail moderate to high risk, which is the appropriate level for NASA R&T.

Not surprisingly, all of the top 10 Challenges involve gas turbine engines, with a strong focus on subsonic operations, the only flight regime currently supporting commercial capacity. V/STOL propulsion systems rank high for their potential to improve capacity, but this will not happen unless significant improvements are made in noise, fuel economy, and reliability. The top 10 Challenges will increase the efficiency of future aircraft, with greater levels of systems integration and optimization offering benefits not possible on aircraft designed component by component. Advances in information technology will lead to intelligent propulsion systems that invoke variability to optimize mission performance. These advances will increase demand for onboard electrical power, which will require electric power generation and distribution systems with more power and higher efficiency. Global air transportation is unlikely to be permanently confined to subsonic flight. Supersonic propulsion technologies will have strong synergies with DoD supersonic aircraft and space launch missions. In addition, many supersonic technologies will also be used to improve the performance of subsonic aircraft components and systems.

Combined-cycle hypersonic propulsion systems are expected to enable reusable launch vehicles with higher payload fractions and to benefit DoD as well.

The following four R&T thrusts describe threads of commonality among the R&T Challenges in the propulsion and power Area:

- High-temperature materials and structures.
- Validated physics-based modeling and simulation.
- Systems integration.
- Intelligent, adaptive systems.

Most of the Challenges in this area, regardless of rank, fall into one of these Thrusts, which are very important and will require significant investment of resources.

High-temperature materials and structures

Advanced materials are a key enabling technology for aeronautical and space vehicles and play a particularly critical role in propulsion systems. New developments in materials and processes for the production of these materials can deliver important improvements in performance, efficiency, safety, and reliability and can enable major advances in engine cycle design. In addition to developing materials with higher use temperatures, there is very significant payoff for high-temperature materials with (1) lower density or higher specific strength, (2) greater resistance to the combustion environment, (3) higher damage tolerance and predictable modes of degradation and failure, and (4) multifunctionality.

Significant NASA investment in materials is absolutely crucial for continued advances in subsonic, supersonic, and hypersonic propulsion and for continued U.S. leadership in advanced propulsion systems.

Gas turbines will continue to dominate civil aviation in the next few decades. Fuel costs, safety, and noise will drive major improvements in efficiency and reliability. Overall efficiency improvements will require higher pressure ratios for the overall cycle, higher turbine inlet temperatures, improvements in fan efficiency, and weight reduction in the large structural engine components. To achieve this, a number of materials developments must occur, including stronger compressor disk materials, higher temperature turbine disk and airfoil materials, and thermal barrier coating systems with higher temperature capability and increased reliability. For larger fan and structural components, low-density intermetallics and improved polymeric composites are needed. Over the past decade NASA has provided leadership and worked cooperatively with engine manufacturers in the development of advanced superalloy turbine disks and single-crystal airfoil alloys that will significantly improve the performance of the next generation of commercial engines. Continued support for research on airfoil and disk materials (including new processing approaches) with temperature capabilities 100°F to 200°F greater than current alloys is a high priority, since a broad exploration of new superalloys, refractory alloys, and intermetallics is beyond the scope and resources of any single engine manufacturer.

NASA has also contributed substantially to the fundamental knowledge base on oxidation of superalloys and coatings and the performance of bond coat/yttria-stabilized zirconia thermal barrier coating systems. Breakthroughs are needed in new ceramics and intermetallic bond coats for thermal barrier coating systems. New testing methodologies should be developed for these coatings to simulate engine environments, including the high thermal gradients that are characteristic of the turbine airfoil.

The development of intelligent engines will also require progress in life prediction, materials diagnostics, and multifunctional materials to enable computation-based life-prediction tools and complementary new approaches to in situ materials diagnostics.

Advances in supersonic and hypersonic propulsion will permit more efficient cross- and intercontinental travel and access to space, respectively. As Mach number increases, propulsion system temperatures escalate rapidly and oxidation becomes a major difficulty, particularly for air-breathing engines. The ceramics, CMCs, and high-temperature metallics (with active cooling) needed for these propulsion systems remain at low technology readiness levels. Materials systems in need of further development include carbon–carbon and carbon–silicon carbide composites, refractory alloys (rhenium-, niobium-, or molybdenum-based), and nickel alloys. Innovation in processing, joining, and close integration of materials with propulsion system design is essential. Significant progress in supersonic or hypersonic flight will require substantial investment in ultrahigh-temperature ceramics, CMCs, and high-temperature metallics. No single U.S. industrial organization has the expertise to make the major breakthroughs in materials that are required.

Validated physics-based modeling and simulation

With the advances in computational speed, power, and affordability of the last two decades, aeronautics researchers have turned increasingly to computational simulation codes to model the complex physical and chemical conditions inherent in aircraft propulsion and power systems. Industry is appropriately enamored of the possibility of using computational simulation to reduce significantly both the cost and time of product development, to optimize system designs, and to increase reliability. Academic and government researchers also value the potential to attack more complex problems. Computational simulations generally employ a number of physics-based models within the governing conservation and state equations. Examples of models already in use include combustion–turbulence interactions, subgrid turbulence models in large eddy simulation (LES) codes, effects of unsteadiness in steady-state compressor codes, reduced-order chemical kinetic mechanisms, and droplet–

flow interactions. These physics-based models often contain adjustable parameters that are grossly calibrated to empirical data sets; the data sets themselves are often incomplete, particularly with regard to boundary conditions, prompting further untested assumptions to be incorporated. The entire codes themselves are often not validated in detail except for comparing their code predictions to input and output measurements. The codes often do not work well when the design space changes considerably, prompting more tweaking of the adjustable parameters. Nevertheless, within their applicable ranges, the computational simulation codes have enabled technical progress, as witnessed by the state of aircraft propulsion today. Unfortunately, the applicable range limits themselves are often not well understood. NASA and its partners can greatly advance aircraft propulsion and power by developing and validating the constitutive physics-based models.

Physics-based models are readily assimilated by industry into their proprietary product system design codes. Research into physics-based models can be conducted jointly by NASA, industry, and academia since it is fundamental in nature, publishable, and shareable. It is work that takes time to mature, yet advances can readily be translated into practice as they occur. Validation involves the design of experimental facilities of appropriate scale and the use of advanced, nonperturbing diagnostics to measure parameters accurately in space and time to rigorously ascertain model fidelity. It is an iterative process culminating in submodels whose accuracy and range of applicability are well established.

Systems integration

This R&T Thrust is intended to support a clear trend in aeronautics design—namely, the movement toward aircraft system-level integration and optimization of traditionally separate airframe and engine subsystems. Improved systems integration will increase capacity by increasing operating flexibility, enabling the use of shorter runways (by improving the performance of powered lift or thrust vectoring systems), reducing end-user costs, and facilitating the design of commercial supersonic aircraft. Efficiency and safety will also be improved by more functional designs that are robust against adverse operational conditions (icing, wake ingestion, foreign object damage, and temperature extremes). "Integration" in this context refers to the physical, functional, and requirements integration of key propulsion and power components with each other, and with other systems, such as the airframe, the avionics, and the overall air transportation system. Optimization of key metrics (cost, weight, thrust, and fuel consumption) at the system rather than the component level is also included in this Thrust.

Integrated power and thermal subsystems were discussed under R&T Challenge B6b. A second example of the systems integration Thrust can be seen with the inlet and exhaust systems that will be required for innovative air platforms. Blended wing-body concepts have been proposed that use boundary-layer-ingesting engine inlets. This approach reduces the performance of the propulsion system but more than compensates for that loss with vehicle improvements in lift and drag. Similarly, although a variable-cycle engine for supersonic cruise might be heavier than a fixed-cycle engine of comparable thrust, it could also eliminate the need for heavy airframe-mounted, inlet-variable geometry, thereby increasing overall vehicle T/W. A higher degree of systems integration should be evident from the earliest design phases and may necessitate entirely new aircraft or engine architectures. New process modeling and simulation tools, along with business models, must also be developed to enable design and validation of integrated systems in a seamless, multiple-organization environment.

Intelligent, adaptive systems

The development of intelligent, adaptive systems technologies will be a key enabler for civil and military aeronautics and space. These technologies will permit (1) real-time, low-latency health monitoring systems; (2) optimization of the performance of current propulsion systems according to mission requirements and environmental conditions, including active control to enhance performance and avoid anomalous behavior; (3) new sets of tools for extended life and improved maintenance of commercial and military fleets; and (4) totally innovative systems for the future. These technologies involve engine and propulsion systems modeling; improved sensor capabilities; and innovative software for control logic that adjusts engine performance to enhance stability, improve distortion tolerance, minimize noise and emissions, and address deterioration issues in service.

Intelligent, adaptive systems are coming online, principally for the health monitoring of both commercial and military engine systems. This capability will anticipate and prevent failures, using control logic to reconfigure engine operation. This capability will improve time on wing, improve readiness, and reduce operating costs. Intelligent engine technologies are essential to the creation of variable-cycle engines. These engines use variable geometry to optimize performance for the mission takeoff, climb, cruise, descent, and landing.

Intelligent, adaptive technologies are needed to reduce fuel consumption and environmental impact by morphing the aircraft or engine to suit the needs of the moment—for example, a takeoff configuration to address noise requirements and a cruise configuration optimized for fuel burn and low NO_x emissions at altitude. Similar technologies will also be used to optimize supersonic and hypersonic engine configurations. For example, intelligent, adaptive engine technologies can be used to optimize a low-noise configuration for takeoff with high bypass ratios and then transition into supersonic or hypersonic configurations. These technologies also have direct application to space vehicles.

Intelligent, adaptive technologies need to be developed for current and future propulsion systems. With current systems, knowledge management should be developed in areas of software control to provide real-time assessment of the remaining life of critical engine components. In new systems, active control and variable geometry should be used to tailor propulsion flows to reduce sensitivity to inflow distortion, to enhance compressor stability, to control exhaust jet area and vector angle to reduce noise and emissions, and to enhance vehicle performance through powered lift.

Low-Priority R&T Challenges

R&T Challenges B11 and B13 ranked in the top 10 in terms of national priority but not by NASA priority. Challenge B11 (alternative fuels and additives for propulsion that could broaden fuel sources and/or lessen environmental impact) is clearly an important national priority. It was ranked lower as a NASA priority because DOE will need to take the lead in establishing the national infrastructure for an alternative fuel and because the combustion research needed to develop such a fuel will take much less time putting an alternative fuel infrastructure in place. Furthermore, aviation fuels are likely to have a first call on petroleum supplies should they become scarce, so that the use of alternative fuels for aviation is likely to follow their widespread use for ground-based applications, which would place less stringent demands on weight, volume, reliability, safety, and certification of new systems and technologies.

Challenge B13 (improved propulsion system tolerance to weather, inlet distortion, wake ingestion, bird strike, and foreign object damage) is ranked low in terms of NASA priority because the relevant technologies are more mature (and the attendant risk lower) and it is not as relevant to NASA s mission as the Challenges that scored in the top 10 by NASA priority.

MATERIALS AND STRUCTURES

Introduction

Advances in civil aeronautics materials and structures technologies are often the key enablers for new modalities of operation or regimes of flight. For example, improving jet engine efficiency requires continual introduction of new materials to allow the implementation of advanced aerodynamic concepts and higher operating temperatures to increase propulsion efficiency. A comprehensive multiphysics understanding of materials and structures enables innovative designs. New analysis techniques produce the next generation of design tools, which will allow revolutionary structural concepts to be accelerated into applications.

The assessment of R&T Challenges related to materials and structures was influenced by the globally competitive nature of the aerospace industry, particularly in the civilian aircraft market. New material and structural technologies that would help U.S. industry establish a clear advantage over its global competitors received high marks. R&T Challenges were also ranked bearing in mind global needs in aeronautics. Growth in demand for the movement of passengers and goods, especially against a backdrop of rapid economic development in Asia, calls for significantly increased capacity in the air transportation system. Similarly, environmental concerns related to fuel efficiency led to a focus on materials and structures Challenges for engine development and harvesting of energy from structural components and systems. Improvement in structural performance and efficiency was another key driver, and the assessment focused on design methods and tools required to facilitate such improvement. The changed climate for national and international security was another important factor.

The QFD process described in Chapter 2 was used to prioritize 20 R&T Challenges related to materials and structures. Table 3-3 and Figure 3-5 show the results. The text that follows describes the 10 R&T Challenges that ranked highest in terms of NASA priority, the general characteristics of high- and low-priority Challenges, and the R&T Thrusts in this Area. Further details on all Challenges, including the rationale for scoring, are found in Appendix C.

Top 10 R&T Challenges

C1 Integrated vehicle health management

Integrated vehicle health management (IVHM) refers to monitoring, assessing, and predicting the health[6] of aircraft materials and structures using networks of sophisticated onboard sensors. A fully integrated approach to IVHM relies on a multidisciplinary set of analysis, testing, and inspection tools, including miniaturized sensors and distributed electronics; sophisticated signal processing; data acquisition, integration, and database maintenance; artificial intelligence; damage science; and the mechanics of structures and their failure.

IVHM benefits all classes of aircraft, in all speed regimes and phases of flight. With a national fleet of aging aircraft and infrastructure in an industry with low profit margins, IVHM is increasingly important due to its ability to increase safety and reliability. It can also have a number of benefits for capacity. Decreasing the possibility of unexpected failure could speed the introduction of innovative material systems and structural concepts and enable the use of traditionally high-maintenance (and high-cost) systems, such as rotorcraft. More data would allow better understanding of the stresses experienced by a system, reducing the amount of overdesign motivated by uncertainty. In addition, aircraft could report the predicted lifetimes of their own parts and

[6]"Health" in this context implies either an absence of measurable material flaws or an ability to coordinate the growth rate of flaws with the safe life remaining for the element in question.

TABLE 3-3 Prioritization of R&T Challenges for Area C: Materials and Structures

		Strategic Objective							Why NASA?					
		Capacity	Safety and Reliability	Efficiency and Performance	Energy and the Environment	Synergies with Security	Support to Space	National Priority	Supporting Infrastructure	Mission Alignment	Lack of Alternative Sponsors	Appropriate Level of Risk	Why NASA Composite Score	NASA Priority Score
R&T Challenge	**Weight**	**5**		**3**		**1**			**$^1/_4$ each**					
C1	Integrated vehicle health management	9	9	3	1	9	3	**114**	9	9	1	9	**7.0**	**798**
C2	Adaptive materials and morphing structures	9	3	9	3	9	3	**108**	9	9	1	9	**7.0**	**756**
C3	Multidisciplinary analysis, design, and optimization	9	3	9	1	3	3	**96**	9	9	3	9	**7.5**	**720**
C4	Next-generation polymers and composites	9	3	9	1	9	3	**102**	9	9	1	9	**7.0**	**714**
C5	Noise prediction and suppression	9	1	3	9	3	1	**90**	9	9	3	9	**7.5**	**677**
C6a	Innovative high-temperature metals and environmental coatings	3	9	3	1	9	3	**84**	9	9	3	9	**7.5**	**630**
C6b	Innovative load suppression, and vibration and aeromechanical stability control	3	9	3	1	9	3	**84**	9	9	3	9	**7.5**	**630**
C8	Structural innovations for high-speed rotorcraft	9	1	3	1	9	1	**72**	9	9	3	9	**7.5**	**540**
C9	High-temperature ceramics and coatings	3	1	9	3	3	9	**68**	9	9	3	9	**7.5**	**510**
C10	Multifunctional materials	3	3	9	3	9	9	**84**	3	9	3	9	**6.0**	**504**
C11	Novel coatings	3	9	3	3	1	1	**80**	3	9	3	9	**6.0**	**480**
C12	Innovations in structural joining	3	3	9	1	3	3	**66**	3	9	3	9	**6.0**	**396**
C13	Advanced airframe alloys	9	1	9	1	3	1	**84**	1	3	1	9	**3.5**	**294**
C14	Next-generation nondestructive evaluation	3	9	1	1	3	1	**70**	3	9	1	3	**4.0**	**280**
C15	Aircraft hardening	1	9	1	1	9	1	**66**	3	3	1	9	**4.0**	**264**
C16	Multiphysics and multiscale modeling and simulation	3	3	3	3	3	1	**52**	3	3	3	3	**3.0**	**156**
C17	Ultralight structures	3	1	3	1	3	3	**38**	3	9	1	3	**4.0**	**152**
C18	Advanced functional polymers	1	3	1	1	3	1	**30**	9	3	3	3	**4.5**	**135**
C19	Advanced engine nacelle structures	3	1	3	1	1	1	**34**	1	9	1	3	**3.5**	**119**
C20	Repairability of structures	3	3	3	1	1	1	**44**	3	3	1	3	**2.5**	**110**

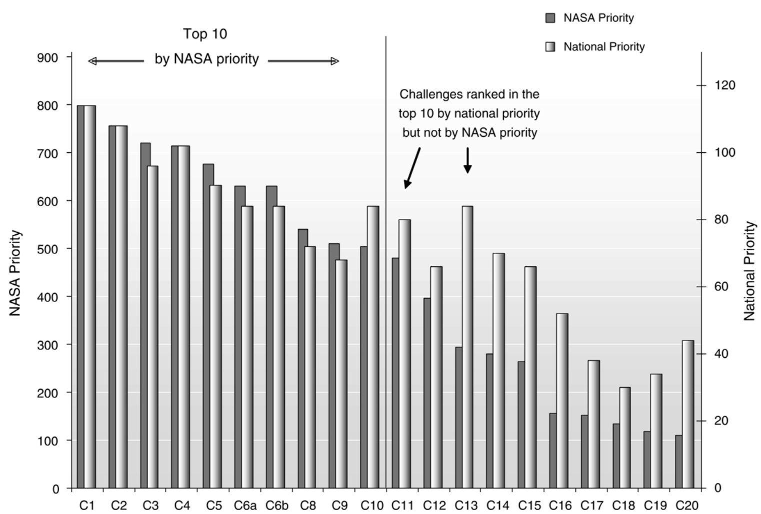

FIGURE 3-5 NASA and national priorities for Area C: materials and structures.

report the need for replacement parts, reducing operating costs and maintenance downtime. IVHM could quickly diagnose root problems, minimizing flight delays and increasing capacity (Powrie and Fisher, 1999; Simon, 2000). IVHM may also reduce vehicle operating cost and maintenance downtime and can speed the introduction of innovative material systems and structural concepts. Real-time onboard sensor systems that monitor the actual state of materials and structural components enable more efficient use of materials, including novel concepts.

There are two main features of the next generation of IVHM: (1) Sensor packages will be very small and exceedingly lightweight and (2) the reliance on humans to interpret the sensor output and assess the impact on structural integrity will be reduced or eliminated.

Three classes of IVHM systems warrant attention over the next decade, culminating in flight testing of full-scale IVHM systems that detect multisite damage. The first class includes fiber-optic sensor systems that use multiplexed fibers attached to or embedded within the structure, each with numerous sensing sites interrogated in turn by a single electro-optic module. The second class includes locally self-powered, wireless microelectomechanical sensors tiny enough that very large numbers of sensors become practical. Each sensor mote performs a point measurement, so many are used to effectively cover large areas. The third class includes discrete active and passive remotely powered sensor modules (e.g., by means of guided-wave ultrasonic or acoustic emission) that may be large compared to sensor motes but can interpret multimode vibrations or multiphysics parameters (temperature, stress, humidity, etc.) that propagate over relatively long distances within the key structural elements.

Successful application of IVHM also relies on continued research and refinement in fundamental structural mechanics and the mechanics of damage and failure for accurate interpretation of IVHM sensor data and to support autonomous decision making for damage recovery and mitigation.[7]

C2 Adaptive materials and morphing structures

Use of adaptive materials and morphing structures to change the aircraft shape (outer mold lines) and functions on demand represents a revolutionary approach for enabling optimal performance over a range of flight missions. Morphing wings that change their planform area by up to 50 percent and alter their sweep angle up to 50 degrees are emerging as a viable technology, and the benefits would be

[7]See R&T Challenges D4 and D5.

far more than the simple variable-sweep configurations of the past. However, the costs of incorporating such technology have not yet been evaluated.

During the past 2 years, two prototypes from the Defense Advanced Research Projects Agency (DARPA) Morphing Aircraft Structures program were successfully tested at transonic speeds in NASA Langley s Transonic Dynamics Tunnel at a scale sufficient to validate the concept. This design included concepts such as stretching skins, sliding skins, and seamless camber change. DARPA has also sponsored flight research of morphing technologies applied at the system level. These tests identified critical long-pole, component technologies that now limit the use of morphing technologies, particularly in heated supersonic flow. Adaptive materials have emerged as the number one component technology need for morphing aircraft. These materials have the ability to radically change the properties of component materials, to facilitate both effective load-carrying abilities and ease of actuation from one shape to another, as well as to change the structural shape, from large variations in wing area to seamless camber-changing.

Adaptive materials may be self-actuated by energy inputs such as light, heat, and electric or magnetic fields. They include heat-activated shape memory alloys like NiTiNOL; ceramics (e.g., lead zirconate titanate); photonically activated, lightweight, flexible shape memory polymers; electrically activated piezoelectrics; and magnetorheological fluids.

This Challenge requires development of commercial, high-speed, morphing airframe concepts, development of structural components such as stretching skins, and accelerated development of a special class of actuatable adaptive materials with lifetimes comparable to those of currently used materials. A fundamental task is to characterize the mechanical response of these inherently nonlinear materials, including hysteresis, fatigue, long-term behavior, and damage behaviors. Analysis and design tools that accurately predict these responses will open the door to even more applications of these revolutionary adaptive structural concepts, which could optimize performance and expand the flight envelope.

C3 Multidisciplinary analysis, design, and optimization

Methods for simulation-based, multidisciplinary design and optimization (MDO) are at the very core of a philosophy that moves away from the build-test-build approach, which has proven to be expensive and ineffective in exploring the aeronautical design space. MDO processes develop synergistic benefits by integrating people, analytical tools, experimentation, and information to design complex structural components and systems (Sobieszczanksi-Sobieski and Haftka, 1997). These approaches allow for development of optimal configurations, topologies, and dimensions for structural members and components to achieve design objectives, and they permit designers to examine the myriad what-if s that characterize sophisticated designs with interdisciplinary trade-offs.

After almost two decades of R&D, MDO processes for conventional designs have reached a high level of sophistication. In structural designs where the topology or outer mold lines are defined, analytical methods such as the structural finite-element technique, coupled with similar analytical tools for load assessment, provide a high level of success. However, for designs with a multiplicity of topologies, some of which are not well-defined, and for problems where a large number of design parameters and constraints must be considered in the early stages of the design process, MDO methodologies are still underdeveloped (Giesing and Barthelemy, 1998). Major effort must also be directed at including the effects of uncertainty in the design process, as well as increasing the level of detail in representing the structure. New ways of formulating problems that incorporate quantitative reliability measures to facilitate effective design decisions have been considered in this context. The extension of these approaches to large-scale structural and material design problems represents an entirely different level of problem complexity.

Significant new developments are required in both the platforms and the embedded tools that constitute the MDO process. Efficiency and effectiveness of the search process continue to be a problem, particularly in large-dimensionality problems and multimodal or disjointed search spaces. Current platforms are ill equipped to efficiently parse the vast amounts of data associated with the design process. There is a marked need for developing analysis modules for the search process to query in the design process. Such analysis modules must be based on the physics of the problem or on inferences derived from experimental data. While digital designs have enabled tight manufacturing tolerances and manufacturers can incorporate cost models, explicit mathematical modeling of manufacturing processes, repair, and environmental impact must be better integrated into the MDO process. These analysis tools must be developed at multiple levels of granularity and precision, to coincide with the appropriate stage of the design process. The numerical efficiency of these tools is paramount, and alternative paradigms that take advantage of a new generation of parallel computational hardware must be sought (Giesing and Barthelemy, 1998; Sobieszczanksi-Sobieski and Haftka, 1997). Uncertainty modeling in a data-lean environment, specifically for new concepts, continues to be an issue in this regard. There is a similar dearth of computationally efficient methods for reliability assessment, particularly in situations where uncertainty distributions do not conform to standard forms or where components or elements exhibit discrete behavior. The propagation of uncertainty in complex and highly coupled multidisciplinary systems needs to be modeled, and tools for design and optimization in a nondeterministic environment continue to be computationally intractable, especially when applied to design problems involving a large number of nondeterministic variables, parameters, and design constraints. Furthermore, the inclusion of risk and reliability analysis in the design process would yield a time-dependent description of risk associated with structural and material systems in service, facilitating decisions that enhance vehicle availability and reliability.

Use of commercial tools in optimization is not enough to advance the state of the art in MDO. Optimization is only one piece of the analysis, design, and optimization triad. It is the tightly integrated development of analysis and optimization tools that furthers the potential of MDO methods. In the aerospace arena, such expertise is unique to NASA. Additional gains can be realized with NASA working in close collaboration with researchers from academia and industry. A number of synergistic benefits could also be achieved by developing this aspect in concert with health-monitoring technologies (see R&T Challenge C1).

C4 Next-generation polymers and composites

Over the past 50 years, polymeric composites have revolutionized and improved the performance of aircraft structures. Future needs for enhanced structural performance, high-temperature capability, and durability can only be met by the next generation of polymer-based composites. Next-generation composites will take advantage of improved high-temperature polymeric matrices, new reinforcement materials, hybrid reinforcement approaches, improved joining technology, and science-based manufacturing with controlled 3-D placement of reinforcements. This Challenge includes development of tougher, higher-temperature adhesives for joining, innovative fillers to enhance performance, and new core materials for ultralightweight sandwich construction. It also includes development of repair techniques to restore structural integrity to damaged composite structures. The development of next-generation composites is dependent on three capabilities: multiscale modeling that links nano- and microstructure to structural composite response; science-based processing techniques that account for resin chemistry, cure kinetics, and flow physics to guide placement and distribution of the different reinforcement phases; and structural and mechanical testing to evaluate both the design and processing parameters. This next generation of composites will significantly improve structural efficiency, safety, and high-temperature performance; reduce data scatter; increase damage tolerance (e.g., delamination); and improve manufacturability (e.g., by eliminating hand lay-up). These composites will likely incorporate adaptive materials and multifunctional concepts, thus providing the enabling materials needed for visionary concepts in nacelle components, wing structures, and fuselage materials.

C5 Noise prediction and suppression

Local communities in this country and abroad are becoming extremely aggressive in passing stringent noise regulations, in order to substantially reduce the impact of aircraft noise. Takeoffs and landings at many airports have been restricted. The ability to reduce aircraft noise thus becomes an environmental as well as an operational constraint. Regulations passed recently in the European Union regarding noise inside commercial aircraft point to the need for cabin noise control as well as external noise control. There are a variety of promising materials and structures approaches that could be developed and validated in the next decade to substantially reduce both exterior and interior noise.

Noise is a multidisciplinary phenomenon. Effective noise control techniques must take into account multiple types of aerodynamic and acoustic excitations. Therefore, structural prediction tools must be integrated with computational aeroacoustic and fluid dynamic prediction tools for a fully coupled solution to the problem of structural noise. To validate these predictions, systematic tests should be carried out to measure noise signatures for a range of flight conditions in controlled environments such as anechoic wind tunnels. This should be followed by selective flight test of full-scale systems to measure noise signatures from the ground as well as inside the airframe.

Advanced materials for larger, stronger fan blades and higher-temperature turbine blades, together with the development of very-high-bypass-ratio engines, will be the biggest single factor in reducing external noise produced by jet aircraft. Advances in strong, lightweight composite nacelle structures, smart materials, and active structures would also reduce engine noise. Variable-geometry-chevron nozzles, which could be driven by the shape memory alloy NiTiNOL, have been demonstrated to reduce noise during takeoff and then reconfigure themselves to a more efficient shape for cruise (Calkins and Butler, 2004).

Major strides in noise suppression can also be achieved using advanced materials and active and passive structural techniques. Promising approaches include nanotechnology to enhance structural damping (noise absorption); morphing or tailored structures for laminar flow and noise source control; and multifunctional active composite structures with improved noise signature control, structural strength, health monitoring, and thermal insulation. The structural weight of additional materials or devices used for noise suppression is a key factor; with expanding advancements in smart structures technology and rapid miniaturization in data processing techniques, active noise control within the aircraft cabin appears more promising. Development of both sorts of noise suppression devices will be a key step to quieting current aircraft (interior and exterior) and could provide an impetus for an explosion of civil applications of rotorcraft and fuel-efficient prop-rotor aircraft.

C6a Innovative high-temperature metals and environmental coatings

Advanced high-temperature metallic turbine material systems (i.e., alloy substrates for the turbine blade, disk, and shroud, plus necessary environmental coatings) are critical to advancing the next generation of jet engines. These engines will power future subsonic and supersonic fixed-wing airplanes and rotorcraft, while enabling reduced operating costs and improved engine safety and reliability. Metallic material systems with higher operating temperatures will improve engine cycle efficiencies. Dramatic improvements in these materials are possible, but development has been retarded by the high cost of R&D given the current highly iterative nature of alloy design. For instance, intermetallic silicides may enable considerably higher operating temperatures than nickel superalloys; advanced disk alloys may greatly reduce creep and fatigue; and protective coatings with superior resistance to environmental degradation could significantly extend the service life of hot section components. But the length of time to develop these materials, often a decade or two, and the risk that success will not be achieved have been a huge disincentive to aggressive development.

The most difficult technical issue is the need to develop material systems that possess improved performance at higher temperatures while maintaining stability for tens of thousands of operating hours in an environment that is highly oxidative, corrosive, and erosive. However, strides are being made in materials modeling capability, driven by the success of new computational tools and ever-increasing desktop computer processing capability. The application of models to guide the advancement of these materials is just beginning, but it is becoming apparent that these tools can cut development time by half and focus alloy development on the most promising approaches, reducing development risk and cost (NRC, 2004). The drawbacks to new material development would be obviated by the ability to replace experiments with computer simulations, as is done with computational fluid dynamics. The goal of this Challenge is to provide the underlying technologies for material modeling tools that can predict properties of new high-temperature metallic materials and associated protective coatings. The effort would include generation of the necessary fundamental data, complemented by testing that simulates realistic jet engine operating conditions to validate the models. In concert with industry, these tools would then be applied to the development of innovative propulsion materials.

C6b Innovative load suppression, and vibration and aeromechanical stability control

This Challenge will minimize the impact of vibratory loads in aircraft using innovative passive and active techniques. It will also examine innovative techniques to increase aeromechanical stability margins in all flight modes.

Current aircraft use numerous passive devices to increase passenger comfort and to safeguard the functioning of key structural components and instruments. Some modern rotorcraft, such as the Sikorsky S-92 and Bell-Boeing V-22, have made successful use of active vibration control, as well. Additionally, the flight envelope is sometimes restricted due to low stability margins for some aircraft. The objective of this research is to couple advanced CFD methodology with comprehensive structural analysis, including multibody formulation, nonlinear structural and inertial couplings, and interactions between the flow and the structure to predict aeromechanical stability, vibratory loads, and vibration signatures at different stations in the airframe. To validate predictions, systematic tests in wind tunnels should be carried out using dynamically scaled and full-scale models to measure vibration loads and damping of different modes for a range of flight conditions. Selective full-scale flight tests should be carried out to measure vibratory loads and stability at level and maneuvering flight conditions. Innovative active and passive techniques should be developed to minimize vibration and increase stability margin. Finally, multidisciplinary optimization should be exploited to develop efficient, low-vibration, aeromechanically stable aircraft.

C8 Structural innovations for high-speed rotorcraft

One revolutionary vision is a next-generation, high-speed, high-lift rotorcraft that can cruise at over 250 knots, and that is "neighborly" quiet, runway independent, and economically competitive with a Boeing 737 aircraft (Johnson et al., 2006). Advances required to achieve such a vehicle include innovative rotor designs, active vibration and load control, variable-speed rotor technologies, active noise control, rotor morphing, lightweight and crash-absorbing airframe technologies, advanced composites with high damage tolerance, advanced transmission systems, diagnostics and prognostics of drive trains and rotor head systems, increased autonomy and maneuverability, and enhanced handling qualities. Reliable, comprehensive aeromechanics and technology tools must be developed and validated systematically, through dynamically scaled and full-scale tests in wind tunnels. This vision provides opportunities to incorporate many disruptive and nondisruptive technologies in rotorcraft design, with an enormous payoff in performance and life-cycle cost compared with existing helicopters.

C9 High-temperature ceramics and coatings

Advanced structural ceramics, including oxide-, carbide-, nitride- and boride-based systems, are characterized by high strength, stiffness, hardness, corrosion resistance, and durability. Such ceramics retain these properties at high temperatures, making them ideal for a wide range of demanding applications, including engine components for subsonic aircraft (combustor liners, exhaust-washed structures, high-temperature ducts, heat exchangers, and nacelle insulation) and airframe and propulsion systems for high-speed vehicles. The primary benefit of structural ceramic materials is the ability to withstand higher temperatures, which improves propulsion system efficiency, increases lifetime, enables higher operating speeds, and expands the margin of safety in airframe applications (NRC, 1998).

Oxide composites with operating temperatures as high as 1250°C and lifetimes of thousands of hours in highly oxidizing combustion or reentry environments are very suitable for some engine components, warm structures, and thermal management components.

Nonoxide composites made of silicon carbide reinforced either with carbon fibers or a combination of carbon fibers and silicon carbide fibers are capable of operating temperatures of 1300°C-2000°C for short times in highly oxidizing environments or for much longer times near the lower end of the thermal range when protected with environmental barrier coatings. Furthermore, because nonoxide fibers exhibit higher strength and better strength retention than oxide fibers, they are being widely researched for application in combustion environments as well as for hot structures of hypersonic and reentry vehicles.

Refractory metal (e.g., hafnium or zirconium) carbides and borides are capable of surviving thermal excursions up to 2000°C-2500°C for short times with little material recession, making them a strong candidate (in either monolithic form or as a composite matrix) for the sharp leading edges of hypersonic vehicles.

During the last 10 years, significant progress has been made in the processing, development, and demonstration of many ceramic systems for specific applications. Oxide composites deriving damage tolerance from highly porous matrices have been commercialized, and other systems with novel fiber coatings have been demonstrated in subscale testing for reentry vehicle thermal protection systems. Silicon carbide matrix processing approaches have advanced significantly, with systems produced by chemical vapor infiltration, melt infiltration, and preceramic polymer infiltration all having been demonstrated in subscale testing for jet or rocket engine components. NASA Glenn has led efforts to fabricate and test jet engine components such as exhaust nozzle liners, combustor liners, and turbine airfoils with silicon carbide matrix composites. Rocket nozzles fabricated from silicon carbide materials have been rig tested, and NASA Ames has demonstrated the ability to reproducibly fabricate refractory metal carbide and boride systems. Despite the above successes, component fabrication is not often taken much beyond the prototyping stage. Advancing the state of the art for high-temperature ceramics suitable for aeronautical applications requires research in several key areas: fabrication and testing; modeling; and attachment methods.

Insufficient fabrication and testing experience deprives designers of confidence in the long-term behavior of these materials and in the design rules for translating material characteristics into component designs. Modeling tools to predict component life for these materials are inadequate. This causes inaccurate performance and cost assessments and further limits the use of ceramic materials. Since these materials are only considered for niche applications, no economy-of-scale cost savings can be anticipated. This could be alleviated through the development of better design tools, a more thorough understanding of the effects of process variations, and more efficient approaches to commercial fabrication.

Work is also needed to develop robust methods of attaching hot components to warm and cool structures as well as to develop textile approaches that can integrate complex component architectures with key features such as stiffeners, sensors, and cooling features.

C10 Multifunctional materials

Materials that possess multifunctional behavior combine electronic, magnetic, chemical, thermal, and mechanical properties at the macro, micro, or atomic level. These materials present unique opportunities for integrating communication, actuation, sensing, self-healing, and energy-harvesting functionalities into lightweight, load-bearing structures. Multifunctional materials enable a wide range of benefits, including improved aircraft telecommunications (wired, wireless, and optical); enhanced potential capabilities and flexibility for electronic and optoelectronic platforms, such as agile phased array and multifunctional radar systems; structural prognosis and nondestructive evaluation; self-sensing and self-repair; and local power generation through energy harvesting. The use of structural elements to provide new functions to aircraft platforms increases structural efficiency and enables new aircraft capabilities.

While the most research to date has been on materials with coupled electromechanical domains, a much broader vision is possible. Recent discoveries of electrochromic, magnetoelectric, and thermomechanical materials show substantial promise for future multifunctional materials.

High-Priority R&T Challenges and Their Associated Thrusts

High-priority R&T Challenges in the materials and structures Area had major relevance to at least one of three high-priority Strategic Objectives: capacity, safety and reliability, and efficiency and performance. Most of the Challenges in this Area were judged to have little or no relevance to energy and the environment, which is the fourth highest-priority Strategic Objective, although one was judged to have major relevance.

The most highly ranked R&T Challenges are those that could radically change the way new aircraft are designed, manufactured, and maintained. The key to success for all of these Challenges is interdisciplinary collaboration. Such a strategy will derive full benefit from NASA s extensive infrastructure in (1) materials development and characterization and (2) structural analysis, optimization, and testing. For example, the highest priority materials and structures Challenge is integrated vehicle health management (IVHM). Success will require a multidisciplinary set of analysis, testing, and inspection tools, including miniaturized sensors and distributed electronics; sophisticated signal processing; data acquisition, integration, and database maintenance; artificial intelligence; damage science; and the mechanics of structures and their failure. Multiple aspects of materials science, structural design, and aeronautics are brought to bear on the problem of assuring vehicle health. IVHM holds the promise of reducing vehicle cost, weight, and maintenance downtime as well as speeding the introduction of new material systems and structural concepts. In addition, IVHM has the strongest influence on both of the most highly weighted Strategic Objectives: improved capacity and enhanced safety and reliability.

Four R&T Thrusts describe threads of commonality among the R&T Challenges within the materials and structures Area. Most of Challenges in this area, regardless of rank, fall into one of these Thrusts, described below.

Visionary materials and structures concepts

Visionary aeronautical concepts often depend on new materials that possess unprecedented properties or behavior and allow aircraft designers to consider new flight regimes, aircraft configurations, and operational paradigms, such as high-speed rotorcraft and morphing aircraft with the ability to change their outer mold lines. Visionary concepts also hinge on innovative structural components, often made possible with newly developed materials, alloys, and coatings. This R&T Thrust is fundamental to NASA s aeronautics mission of enabling revolutionary concepts and innovative designs. New structural concepts take advantage of emerging analytical design tools and advanced structural materials, and they promise to significantly reduce the weight of structures while maintaining structural integrity and improving efficiency. New material concepts include next-generation polymers, metals, and composites, as well as advanced functional polymers and adaptive and multifunctional materials and coatings.

Comprehensive multilevel predictive methodologies for design and analysis

The second R&T Thrust for materials and structures technology is developing and understanding the multiscale and multiphysics behavior of aircraft materials and structures in a comprehensive manner and then bringing together previously separate design and analysis methodologies and tools, starting from the initial design concept all the way through to operation. This thrust moves beyond the realm of existing MDO techniques to incorporate key aspects of risk-based design and reliability. With new tools that allow systematic inclusion of the effects of uncertainty, whether in loading, material behavior, or mission requirements, this process would yield a rational approach for quantifying the risk associated with a certain design and allow for meaningful trade-off studies to be performed among competing design concepts. These tool sets would revolutionize aircraft design by reducing weight, noise, and vibration and by increasing stability control. NASA could have a unique role in developing and benchmarking such tools at the precompetitive stage, prior to their adoption by industry.

Novel technologies for improved structural efficiency and safety

Many of the R&T Challenges for materials and structures relate to improving structural efficiency and safety. Some, like ultralight structures and advanced joining, reduce weight directly. Alternatively, functionality can be added to a structural component or to the materials in the component to increase overall design efficiency. This Thrust includes adaptive structures that change shape and functions on demand, allowing efficient, multipoint adaptability for optimal performance. Also included are materials that perform dual roles in systems by virtue of their ability to serve as structural elements and to generate power, manage thermal loads, or impart some other additional functionality. IVHM, nondestructive evaluation (NDE), and vibration control use advances in sensing and actuation technology to reduce requirements on the structures themselves. This Thrust also includes aircraft hardening (increasing survivability of an aircraft in the event of an explosion or biological or chemical threat), which should enable new levels of safety.

Materials and structures for extreme environments

Materials and structures suitable for use in extreme environments are relevant to many R&T Challenges. Extreme environments are characterized by very high temperatures, chemical reactions, and erosive and/or corrosive conditions. They can be found in engine interiors and in the supersonic and hypersonic speed regimes. Expanding the operational envelope of each class of structural materials (polymers, metals, ceramics, and composite systems) would increase efficiency and safety margins for airframe and engine materials and structures.

Low-Priority R&T Challenges

The QFD process identifies areas of high national and NASA priority. In general, these two scores were highly correlated. However, as seen in Figure 3-5, two R&T Challenges in the top 10 by national priority did not make the top 10 by NASA priorities: novel coatings and advanced airframe alloys.

C11 Novel coatings

Novel coatings had only middling scores when it came to supporting infrastructure available at NASA and lack of alternative sponsors, primarily because these coatings were, for the most part, either underdeveloped or well developed.

Underdeveloped coatings (including self-sensing, acoustically active, and functionally graded coatings) are still in the very fundamental research stage. Rather than focus on them directly, NASA should establish partnerships with universities to develop these coatings. The well-developed coatings (including superhydrophobic and ice shredding coatings) already have significant commercial potential and should be handled by industry.

C13 Advanced airframe alloys

Airframe alloys had low scores in supporting infrastructure and lack of alternative sponsors. Industry has significant interest, resources, facilities, and expertise to address this Challenge, whereas NASA s own capability has eroded owing to the retirement of expert personnel. Several new and promising metallic materials can be used for critical structural applications. NASA can make a significant contribution to developing these alloys by collaborating with universities doing fundamental multiscale physics research necessary to gain a fundamental understanding of their material behavior. This knowledge could then be leveraged with industry s efforts to enable the design of materials for specific properties. This will dramatically shorten the development cycle for new alloys by focusing limited resources on the most promising candidates.

Other low-priority challenges

Some materials and structures R&T Challenges scored low because they did not fit within the decadal time frame that is the scope of this survey, they were already being pursued by industry or other government agencies, or they were not viewed as major contributors to civil aviation. Many of these Challenges address emerging technologies, and relevant research will yield useful products, but their utility to and impact on commercial aviation is either limited or unknown. Most intriguing is advanced functional polymers (Challenge C18), which includes self-healing polymers for passive repair of damage, reversible liquid crystal adhesives, light-harvesting polymers for collecting solar energy, superabsorbent polymers for flame retardation, and mechanochromic polymers that can change color in response to damage. A logical role for NASA in this dynamic and diverse area would be to vet new materials and devices and develop criteria for long-term materials investment.

R&T Challenges such as innovations in structural joining (Challenge C12), advanced airframe alloys (Challenge C13), aircraft hardening (Challenge C15), ultralight structures (Challenge C17), advanced engine nacelle structures (Challenge C19), and repairability of structures (Challenge C20) are also worthy of note since they could improve current civil aircraft design and also apply to military aircraft. In some cases, these Challenges are regarded as natural candidates for company investment, not cutting-edge NASA efforts. Joining, repair, and lightweight design aspects of airframes are also addressed in the highly ranked multidisciplinary analysis and the new composites tasks. Ultralightweight structural concepts benefit from the integration of advanced composites, adaptive materials, multifunctional materials, and multidisciplinary structural optimization. Thus, even though these topics received low rankings on their own, they will be addressed in a broader, integrated context in the more highly ranked tasks.

Similarly, advances in NDE are synergistic and closely allied with IVHM efforts. NDE provides input to prognosis and life-prediction systems, and its development fits well with NASA s mission in terms of aviation safety. NDE facilitates the development and insertion of new materials and structures and processes by ensuring that they are manufactured according to specifications and behave as designed when they are put into service. However, NDE is also an active area of research in DoD and in nonaerospace industries. For the next generation of NDE, the data-acquisition hardware is of less interest than the new tools for interpreting the multiphysics NDE measurement data. NASA should work in collaboration with academia to develop analysis tools for automating the interpretation of the multiphysics NDE measurement data. This role would provide NASA a unique focus, different from the work currently sponsored by others.

Multiphysics and multiscale modeling and simulation (Challenge C16), while important to the efficient design of future materials and structures, has many contributors from several federal agencies as well as academia. It lacks a clear, focused set of objectives and a clear tie to NASA s mission. The long time frame associated with R&D in multiphysics, multiscale modeling makes this Challenge more suited to academia.

DYNAMICS, NAVIGATION, AND CONTROL, AND AVIONICS

Introduction

In this report, dynamics is defined as the motion characteristics of the aircraft due to the forces that act on it. Navigation generally refers to determination of the aircraft s state (i.e., its position, velocity, and attitude rates) in three dimensions at a particular time. Control is closely linked to guidance; together they refer to determination of the aircraft s future state and the processes for reaching and staying on a specified trajectory. Finally, avionics consists of aviation electronics, both onboard and off-, which implements navigation, guidance, control, surveillance, communications, and other functions. Avionics includes the development, production, and use of aviation electronics, including both hardware and software.

The QFD process described in Chapter 2 was used to prioritize 14 R&T Challenges related to dynamics, navigation, and control, and avionics. Table 3-4 and Figure 3-6 show the re-

TABLE 3-4 Prioritization of R&T Challenges for Area D: Dynamics, Navigation, and Control, and Avionics

		Strategic Objective							Why NASA?					
R&T Challenge	**Weight**	**Capacity**	**Safety and Reliability**	**Efficiency and Performance**	**Energy and the Environment**	**Synergies with Security**	**Support to Space**	**National Priority**	**Supporting Infrastructure**	**Mission Alignment**	**Lack of Alternative Sponsors**	**Appropriate Level of Risk**	**Why NASA Composite Score**	**NASA Priority Score**
		5		3		1			1/4 each					
D1	Advanced guidance systems	9	9	9	3	3	3	**132**	9	9	3	9	**7.5**	**990**
D2	Distributed decision making, decision making under uncertainty, and flight-path planning and prediction	9	9	9	3	3	3	**132**	3	9	3	9	**6.0**	**792**
D3	Aerodynamics and vehicle dynamics via closed-loop flow control	1	9	9	3	3	3	**92**	9	9	3	9	**7.5**	**690**
D4	Intelligent and adaptive flight control techniques	3	9	9	3	3	9	**108**	3	9	3	9	**6.0**	**648**
D5	Fault-tolerant and integrated vehicle health management systems	3	9	3	1	3	9	**84**	9	9	3	9	**7.5**	**630**
D6	Improved onboard weather systems and tools	9	9	3	1	1	1	**104**	9	9	3	3	**6.0**	**624**
D7	Advanced communication, navigation, and surveillance technology	9	9	9	3	3	3	**132**	3	9	3	3	**4.5**	**594**
D8	Human–machine integration	3	9	9	1	3	3	**96**	3	9	3	9	**6.0**	**576**
D9	Synthetic and enhanced vision systems	3	9	3	1	1	3	**76**	9	9	3	3	**6.0**	**456**
D10	Safe operation of unmanned air vehicles in the national airspace	3	9	3	1	9	1	**82**	3	9	3	3	**4.5**	**369**
D11	Secure network-centric avionics architectures and systems to provide low-cost, efficient, fault-tolerant, onboard communications systems for data link and data transfer	9	9	9	1	9	3	**132**	3	3	1	3	**2.5**	**330**
D12	Smaller, lighter, and less expensive avionics	1	3	9	3	3	9	**68**	3	3	3	3	**3.0**	**204**
D13	More efficient certification processes for complex systems	3	9	9	1	1	3	**94**	3	1	1	3	**2.0**	**188**
D14	Design, development, and upgrade processes for complex, software-intensive systems, including tools for design, development, and validation and verification	3	9	3	1	1	3	**76**	1	3	1	1	**1.5**	**114**

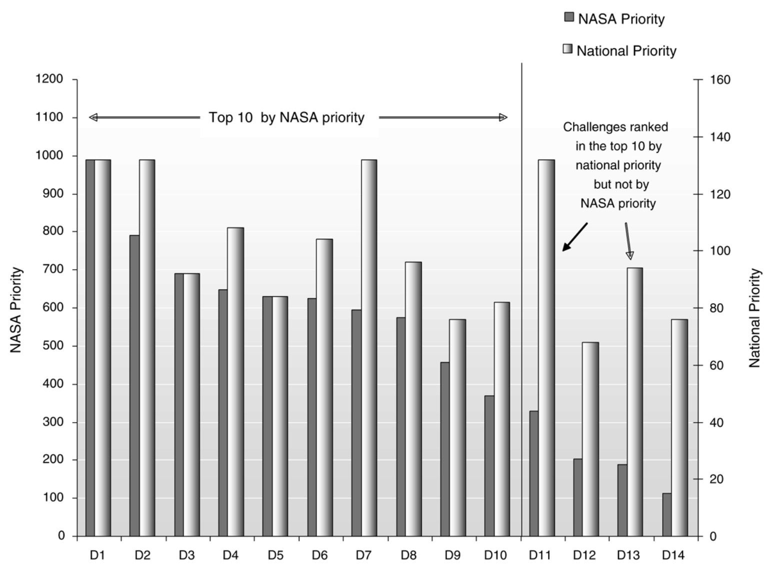

FIGURE 3-6 NASA and national priorities for Area D: dynamics, navigation, and control, and avionics.

sults. This section describes the 10 R&T Challenges that ranked highest in terms of NASA priority, the general characteristics of high- and low-priority Challenges, and the R&T Thrusts in this Area. Further details on all the Challenges, including the rationale for the scoring, are found in Appendix D.

Top 10 R&T Challenges

D1 Advanced guidance systems

Advanced guidance systems consist of subsystems and processes (hardware and software) assembled for the purpose of providing an aircraft, spacecraft, or other dynamic system with desired state trajectories. These trajectories can be defined using either discrete or continuous data and can include information such as current velocity, acceleration, time of arrival, and desired position. The determination of the desired trajectory usually takes into account mission-dependent constraints, which can include obstacles (such as terrain, wake vortices, or other aircraft), hazards (such as weather), coordination with other aircraft (such as cooperative and multiaircraft guidance, formation flight, or swarming), and regulatory constraints (such as airspace class restrictions) (Doebbler et al., 2005).

State-of-the-art guidance systems enable aircraft to follow waypoints, perform automatic obstacle avoidance, and fly in formation with other aircraft (Schierman et al., 2004). Additional research is needed to develop guidance algorithms and mature them into flight-ready systems,[8] to develop improved reconfigurable and adaptive guidance systems, and to develop advanced guidance systems for UAVs. One concern, for example, is the need to develop improved technologies to avoid controlled flight into terrain, particularly in the case of all-weather operation of advanced rotorcraft. Some important research is inhibited by the limited number of programs and facilities capable of implementing and flying these systems on real aircraft. Also, certification and regulatory issues must be resolved so that the air trans-

[8]R. Duren, associate professor, Baylor University, "Avionics research challenges," Presentation to Panel D on November 15, 2005.

portation system can take advantage of the full capabilities of current and future guidance systems for piloted aircraft and UAVs.

Advanced guidance systems have the potential to greatly improve the capacity, safety, and efficiency of the air transportation system. In addition, they can enhance the performance of many existing and future military systems.

D2 Distributed decision making, decision making under uncertainty, and flight path planning and prediction

Improving the decision-making process used by pilots and aircraft systems, when coupled with improvements in flight-path planning and prediction, has been theorized as an effective approach to improving air transportation system capacity and safety. This Challenge has the potential to significantly improve the timeliness of real-time decisions to alter flight paths in the dynamic environment of congested airspace (Ding et al., 2004; Helbing et al., forthcoming; Rong et al., 2002). Coordinated decision making, which includes the direct exchange of data among different aircraft and the deconfliction of flight paths without the need to rely on ground-based controllers, addresses the inherent limitations of centralized air traffic control systems in terms of uncertainty and fault tolerance. A coordinated, distributed approach to decision making increases air transportation system reliability and safety by distributing control and mission management capabilities among multiple agents. It also allows for rapid response to changing dynamics and minimizes vulnerability to system failures.

Automated systems can help improve decision making and flight path planning. Levels of automation ranging from "pilot aid" (that is, systems that advise pilots to take specific action) to "fully autonomous" are achievable but have not yet been developed to the point where they can support high levels of automation for civil aircraft. Until now, coordinated distributed algorithms for constraint reasoning (for example, to optimize flight paths) have not been applied to the air transportation system because implementation with such a complex system would require aircraft to exchange a large number of messages, which raises substantive communications, bandwidth, and man–machine interface issues.

This Challenge should address the needs of a wide variety of conventional and unconventional aircraft types, including those with no distributed decision-making capability. Aircraft types of interest include commercial airliners, general aviation aircraft, civil helicopters, military aircraft, and UAVs.

This Challenge also has the potential to be of great benefit when applied to complex, nonaviation systems that operate in dynamically changing environments and require high-quality, real-time decision making.

D3 Aerodynamics and vehicle dynamics via closed-loop flow control

Closed-loop flow control appears to offer tremendous promise in improving aerodynamic performance. For example, active flow control approaches should allow the airfoil lift:drag (L/D) to remain high over large changes in angle of attack.[9] Flow control R&T could also be used to develop a spoiler-aileron to replace complex and heavy control surfaces and to reduce or eliminate turbulent flow over aircraft surfaces to reduce skin-friction drag. These applications could lead to new aircraft configurations (Chavez and Schmidt, 1994).

The mechanization of flow control systems may require a large number of distributed sensors measuring pressure or shear stress over the wing and changes in the boundary layer. Actuation might be accomplished by morphing the wing or introducing devices that induce sucking or blowing along the wing. These distributed sensors and actuators are coordinated so that control is obtained over large flight regimes, angles of attack, and attitudes.

Distributed sensing and actuation would also permit structures to be self-aware for health monitoring, thereby increasing system reliability. Airframe and engine structures could be monitored for changes in behavior.

Some of the techniques developed by this Challenge may also advance modeling and design capabilities applicable to morphing aircraft (Tandale et al., 2005; Valasek et al., 2005). Heretofore, aircraft have generally been fixed-frame structures. Morphing aircraft would be designed with distributed actuation and controls and with mechanization as an inherent property. They would lead to new capabilities and concepts in aircraft design. Examples include (1) biomorphic aircraft, such as ornithopters, that could maneuver robustly in complex environments and (2) hunter-killer aircraft that change shape to optimize performance for different tasks (e.g., surveillance, reconnaissance, and ground attack). Morphing technology might also enable aircraft capable of perching.

D4 Intelligent and adaptive flight control techniques

The missions and capabilities of future aircraft, both manned and unmanned, will be more multifunctional than those of the current generation of specialized aircraft. Achieving aggressive performance targets in range, payload, reliability, safety, noise, and emissions will require a total system that is integrated to a far higher level than existing aircraft. R&D for military aircraft has been able to push the

[9] The flow over the specially shaped GLAS II airfoil remains naturally separated at the rear of its upper surface over a wide range of angles of incidence; in the absence of active control, its L/D does not exceed 25. At an incidence angle of 10 degrees, its L/D is nearly 500 (Glauert, 1945; Glauert et al., 1948).

technological envelope associated with intelligent and adaptive flight control techniques farther than R&D for civil aircraft because of different safety limits. In the far term, as it advances, application of military technology to civil aircraft may be possible.

The vehicle management systems (VMS) paradigm offers the most promising path to realizing goals related to this Challenge. VMS takes a top-down systems approach to specifying, designing, and validating the aircraft as a single system with highly integrated inner and outer loops. It thereby unifies the traditionally separate fields of propulsion control, flight control, structural control, noise control, emissions control, and health monitoring. The current state of the art in VMS uses traditional feedback control, consisting of measurements of vehicle states such as airspeed, altitude, angle of attack, and linear and angular acceleration (Jaw and Garg, 2005). By incorporating an online learning capability to cope with new and unforeseen events and situations and nonlinear adaptive control, in which the controller self-tunes to maintain stability and tracking in the presence of disturbances and changing vehicle parameters, an intelligent and adaptive VMS can be developed with the promise of significant advances in capability, safety, and supportability (Tandale and Valasek, 2003).

Significant advances in the state of the art are required to develop an intelligent and adaptive VMS. Current nonlinear adaptive control approaches assume that (1) sensor information is reliable and (2) known nonlinearities can be modeled as slowly varying parameters that affect the system linearly. However, advanced actuators for flow control and structural control will have characteristics that are much more nonlinear than those of conventional control actuators. Control laws and control actuator allocation are currently treated as separate problems, such that optimization of the integrated control law is difficult or impossible. Finally, the problem of multiple correlated, simultaneous failures remains unsolved. Approaches that use analytic redundancy to finding failed sensors generally assume that aircraft dynamics have not changed, while adaptive or reconfigurable control approaches assume that sensor information is reliable. On an affordable aircraft with limited or no sensor redundancy, it is difficult or impossible to tell the difference between a degraded sensor and damage to the aircraft that changes the way it flies.

D5 Fault-tolerant and integrated vehicle health management systems

Development of IVHM system technologies is key to the acceptance of the automation needed in the transformation of the air transportation system. The technology provides an increased capability to accurately discover and assess system faults and reconfigure or recover from them. Although highly integrated, health management aspects consist of related components: fault detection and isolation, recovery and reconfiguration, and condition-based maintenance (CBM). In addition, modeling plays an important role in the development of these functions (Garg, 2005; Litt et al., 2005; Tandale and Valasek, 2006).

Fault detection, isolation, recovery, and reconfiguration

Fault detection, isolation, recovery, and reconfiguration involve processes and approaches that enable robust detection of faults from measured or estimated error residuals and isolation of faults with minimal latency in the presence of noise and environmental effects during aircraft operation. Fault detection, isolation, recovery, and reconfiguration are platform specific and should cover all flight regimes and mission types. Recovery and reconfiguration systems are developed with regard to the possibilities of faults, the nature of the latency of the fault detection and isolation system, and the controls available for recovery and reconfiguration. Redundancy management strategies for avionics and the airframe directly influence options for recovery and reconfiguration.

Condition-based maintenance

CBM involves maintenance processes and capabilities derived from real-time assessment of aircraft system conditions obtained by software from embedded and redundant sensors. The combination of software and sensors can create important communications and bandwidth problems. More robust diagnostics and prognostics are needed to achieve the goal of CBM, which is to perform maintenance only on evidence of need to prevent a failure from reducing aircraft availability. In addition, CBM includes processes that couple real-time assessment of system and component performance with ground- and air-based logistics to improve aircraft system readiness and maintenance practices. CBM is a form of proactive equipment maintenance that forecasts incipient failures. CBM also aims to ensure safety, equipment reliability, and reduction of total ownership cost. Fault tolerance is achieved when CBM is married to decision strategies for safe and reliable operation of manned and unmanned aircraft.

Modeling

Physics-based models of sensors, actuators, avionics, components, and vehicle flight dynamics contribute to the development of methods for forecasting aircraft system performance and, thereby, help uncover faults. In addition, these models can be used for examining architectures and control strategies to reconfigure systems and ensure safety and reliability.

An aircraft is a very complex system. While individual fault-tolerant functions can be set up for each subsystem, the value of fault-tolerant designs is maximized when the system is modeled as a whole, since the behavior of each subsystem can influence that of other subsystems. The advantage of working with a total system model lies in the ability to discover a fault through its effects on other parts of the system before the fault is discovered in the individual subsystem itself. One primary thrust of fault-tolerant technology development is to identify system models that characterize the behavior of systems properly without developing an overly detailed and unnecessary representation. In other words, an optimum system is not a collection of optimized subsystems.

To advance the state of the art in fault-tolerant aircraft systems, fundamental R&T is required in the three topics above to develop a more robust image of the state, or health, of an aircraft in the presence of uncertainty. With a better model of itself the aircraft can trace back system anomalies through the multitude of discrete state and mode changes to isolate aberrant behavior. Fault-tolerant systems combine simple rule-based reasoning, state charts, model-free monitoring of cross-correlations among state variables, and model-based representations of aircraft subsystems. Together, these models form a hybrid system model. Advances in computing resource technology have allowed hybrid system models to run in real time.

Fault-tolerant aircraft systems, coupled with CBM, may improve aircraft safety and reduce aircraft life-cycle maintenance and ownership costs. Critical research tasks include developing (1) robust and reliable hardware and software tools for monitoring components, detecting faults, and identifying anomalies; (2) prognosis analysis tools for predicting the remaining life of key components; (3) approaches for recovering from detected faults, including reconfiguration of the flight control system for in-flight failures of manned and unmanned aircraft; and (4) low-cost, lightweight, wireless, self-powered sensors with greater memory and processing capability.

D6 Improved onboard weather systems and tools

Pilots—and the avionics software that provides in-flight four-dimensional trajectory replanning and commands to the pilot or autopilot—require additional weather information to minimize the impact of weather on the control of flight in high-density traffic. Basic research is needed to determine the most cost-effective way of integrating real-time weather information into four-dimensional integrated control of flight. This information might include information from data links with ground sites and other aircraft and weather video from ground stations and satellites (Bokadia and Valasek, 2001; Lampton and Valasek, 2005, 2006).

Other aircraft could provide information about geospatial position, wind, icing conditions, turbulence, lightning, and precipitation, as well as imagery from radars and other sensors. Data links with the ground could provide actual and forecast information on winds at different flight levels, pressure, icing potential, precipitation, ground-level temperatures, weather fronts, severe weather, airport surface conditions, and other information from significant meteorological information reports (SIGMETs); pilot reports (PIREPs); meteorological aviation reports (METARs), terminal area forecasts (TAFs), imagery from satellites and radars, and so on.

D7 Advanced communication, navigation, and surveillance (CNS) technology

The capacity of the air transportation system is dependent on minimum spacing requirements for safe operation. Minimum spacing depends on many factors, including the capability of each aircraft to precisely fly a predetermined, geospatially time-referenced flight path.

Advanced, integrated, accurate, secure, and reliable CNS capabilities are required for network-centric operations, which can increase capacity in very high density airspace. Each aircraft may be considered a node in a network-centric, distributed, fault-tolerant ATM system. Communications between nodes (aircraft to aircraft, aircraft to ground, and aircraft to satellite to ground) must be highly reliable. (For example, the probability of a missed or incorrect message should be less than 10^{-7} per flight hour, depending on the consequence of the fault.) Safe, secure, accurate, and certifiable CNS technologies that provide required capabilities are needed.

More precision aircraft navigation, coupled with the precise six-dimensional[10] guidance algorithms used in advanced flight management systems, will enable reduced spacing between aircraft operating en route and in the terminal airspace. CNS system functions must be tightly coupled in terms of information integrity, and they should allow pilots to operate cooperatively with ground systems without controllers continuously in the control loop. The CNS should transmit navigation, guidance, and other sensor data to other aircraft and ground operation centers via multichannel data links while, at essentially the same time, they receive similar information about other aircraft, the weather, airport conditions, etc. This information can prevent accidents by revealing the current and future status of other aircraft, weather phenomena, terrain, buildings, and vehicles on the ground at airports. This Challenge should also increase the affordability of onboard avionics to encourage aircraft owners and operators to procure more capable avionics. This Challenge encompasses the following CNS issues:

- Communications issues.
- Fault-tolerant network connectivity and security.
- Dynamic network control and reconfiguration.
- Quality of service.

[10]The six dimensions refer to three position coordinates and three velocity vectors to define aircraft location, speed, and direction of motion.

- Spectrum allocation and usage.
- Adequate communication bandwidth.
- Required communications capability as a function of geospatial location and phase of flight.
- Navigation issues.
  —High-precision, six-dimensional estimate of aircraft state as a function of time.
  —Integration of satellite navigation with other navigation modes.
  —Navigation system capability, including reliability and quality of input signals.
  —Functional integration of navigation system with guidance and flight control systems to ensure high-integrity, integrated control of flight during automatic and manual modes.
- Surveillance issues.
  —Capability of data links to provide accurate time-referenced data from navigation systems, guidance systems, and other sensors when interrogated by external systems or periodic broadcast.
  —Handling of multiple, simultaneous interrogations using multiple channels to provide high-integrity, secure data.
  —Processing and reacting to incoming data about other aircraft, hazardous weather, etc.
  —Continuous improvement in situational awareness through advanced sensors, communication links, and human–system interfaces.

D8 Human–machine integration

The ever-increasing demand for air transportation, combined with the rapid pace of technological change, poses significant challenges for effective integration of humans and automation. For the foreseeable future, humans will continue to play a central role in key decision-making tasks that directly influence the efficiency and safety of civil aviation. As technology evolves, it may be anticipated that the role of humans and the nature of their task will change accordingly. In order to maintain or improve on existing standards of performance and safety, it is critical that the allocation of functions between humans and automation and the design of the human–machine interface be optimized based on a solid foundation of scientific principles that reflect our best understanding of human sensory, perceptual, and cognitive processes. Human–machine integration should remain an important element of NASA research directed toward civil aeronautics applications.[11] However, the emphasis should be shifted from development and testing of specific input and output devices toward more fundamental research involving modern instruments that measure brain physiology. Research should also include voice command and recognition technology, coupled with increased machine contextual understanding, to reduce workload. This will help define the future role of humans in complex, highly automated systems. Key research topics include human–machine integration methods, tools, and integration technologies for vehicle applications.

D9 Synthetic and enhanced vision systems

Synthetic and enhanced vision systems provide an out-the-window view of terrain, obstacles, and traffic. These systems can also be used as flight crew interfaces for flight trajectory and planning operations (Kelly et al., 2005). The synthetic vision systems that use databases to generate terrain and obstacles require high-fidelity, high-integrity information and a self-healing capability. Enhanced vision systems use forward-looking sensors such as infrared, radar, and laser ranging to allow the flight crew to visualize the real world when visibility is hindered. Currently, vision systems are limited by weather, human factors issues, and other issues. New sensors and improved sensor fusion are needed.

A combined synthetic and enhanced vision system has future potential as a navigation, approach, and landing sensor. The ability to "see" the airport in poor weather has the potential to reduce the likelihood of a go-around. Information fusion that exploits the capabilities of sensors and compensates for their deficiencies is needed, and the immature state of this art represents the most difficult obstacle to achieving these benefits.

Synthetic and enhanced vision systems are also intended to aid airport surface operations in poor weather, reducing runway occupancy and taxiing errors and reducing gate-to-gate travel time. Research topics of interest are as follows:

- Database integrity and quality.
- Information fusion.
- Object detection and avoidance.
- Human–machine interface issues.
- Verification of accuracy, fault tolerance, and reliability.

D10 Safe operation of unmanned air vehicles in the national airspace

The use of UAVs for a variety of civil applications (e.g., farming, communications relays, border monitoring, power line and pipeline monitoring, and firefighting) will continue to increase. Flight operations of military UAVs in civil airspace are also expected to increase. To facilitate these operations, UAVs should be integrated into the air transportation system. This requires them to be at least as safe as manned aircraft.

Most UAV technologies, capabilities, and processes are shared with manned aircraft and require research in several key topics, including the following four:

[11] J. Vagners, professor emeritus, aeronautics and astronautics, University of Washington, Presentation to Panel D on November 15, 2005.

- *Aircraft*. Automation, system upgrade issues, and communications systems, all of which are distinct from those for manned aircraft.
- *Human–machine interaction*. Function allocation, human interface design, situational awareness, training, and required level of proficiency in the remote operation of the aircraft.
- *Maintenance and support*. In matters where UAVs differ distinctly from traditional aircraft.
- *Flight operations*. Sense- or see-and-avoid issues, person-to-person interfaces between operators and controllers, assurance of positive control of the aircraft (especially with highly automated UAVs that are not directly controlled by ground-based operators in real time), and automated contingency management.

High-Priority R&T Challenges and Their Associated Thrusts

R&T Challenges that significantly impact multiple strategic objectives or for which NASA possesses unique capabilities ranked high on the technology prioritization list. All of the top 10 Challenges received the maximum score for relevance to safety and reliability, and seven of the top 10 also received the maximum score for relevance to capacity and/or efficiency and performance. None of the top 10 received the maximum score for energy and the environment, one received the maximum score for relevance to national and homeland security, and two received maximum scores for support to space. Most of the Challenges, regardless of rank, fall into one of five R&T Thrusts that describe threads of commonality among the R&T Challenges within the dynamics, navigation, and control, and avionics Area. These thrusts are discussed next.

Increased integration

Avionics systems are becoming more integrated within individual aircraft, and the control of aircraft flights is more tightly integrated in the air transportation system as a whole. The future air transportation system will see increased integration and information sharing among components of the air transportation system—including individual commercial, business, and general aviation aircraft; ATM facilities; and operation centers for passenger airlines, air cargo operators, and the military. Capacity increases can be achieved, for example, by reducing separation between aircraft, but this could threaten safety. An individual aircraft requires information on the relative position of other aircraft and ground hazards, which may be fixed (terrain and buildings) or moving (aircraft on taxiways and runways). Functional as well as information integration will be needed. All of this will require fault-tolerant, integrated, secure, reliable, flight-critical communications.

Multifunctional, highly integrated guidance and control

The missions and capabilities of future aircraft, both manned and unmanned, will be more multifunctional than the current generation of specialized aircraft. Achieving aggressive performance targets in range, payload, reliability, safety, and emissions will require aircraft to be much more integrated than existing aircraft systems.

Distributed decision making and control

Most scenarios for the future air transportation system envision increased distribution of decision making. Currently, most decision making is centralized and ground-based, with air traffic controllers responsible for coordinating the movement of aircraft in the air and the FAA center at Herndon, Virginia, responsible for national flow control. While centralization has advantages in terms of ensuring safety, it is inflexible and it limits decision making by the pilots and airlines. It also has inherent limits—for example, the mental limits of individual human controllers—that contribute to capacity problems in the system.

Technological advances such as advanced communication systems, satellite navigation, and sophisticated decision-making technologies could further distribute decision making and control among various airspace systems and move these tasks from the ground to the air. These changes, however, will require much greater complexity and functionality in the airborne systems, and important questions must be answered before these changes can become a reality. Relevant questions include how to ensure safety in such a distributed environment, how to provide reliable and efficient communications, how to develop and implement sophisticated decision-making algorithms, and how to define and implement appropriate human–machine interactions.

Intelligent use of automation

Used intelligently, automation has the potential to greatly enhance the safety and efficiency of civil aviation. The rapid evolution of technologies for sensing, processing, and communicating information enables designers to consider new systems with unprecedented levels of automation. The current trend toward increased automation is introducing fundamental, qualitative changes in human roles and tasks. In some cases, these changes have assigned humans tasks for which they are ill-equipped, such as monitoring highly automated processes.

NASA has substantial facilities and expertise that could be applied to this Thrust. Historically, these resources have primarily been used to develop and demonstrate specific system- and subsystem-level solutions to particular operational or safety problems. Transitioning these point designs to practical applications has been problematic. A more productive use of NASA s considerable capabilities would be for NASA to become a provider of basic research products, enabling technologies, and system engineering tools to support system development by industry and certification by the FAA. There is a compelling need for a focused program of research that will yield practical, validated technologies, processes, and tools to support effective human–machine integration in civil aviation.

Revolutionary vs. evolutionary approaches

Aeronautics research can use revolutionary and/or evolutionary approaches. A revolutionary approach allows the researcher to look for the best solution to a problem (assuming "best" can be properly defined) using the latest technology available without concern for the technology that is currently fielded. The evolutionary approach looks for a solution that is a derivative of or an incremental improvement to a current system.

NASA plays an important role in aeronautics with its capability to do revolutionary research. By following a revolutionary approach to ATM and avionics, for example, NASA can set a goal for the end state—a picture of what the system might look like in 10, 15, or 25 years. NASA can use its modeling and simulation expertise and its proof-of-concept flight demonstration capabilities to predict the system efficiencies for the end state. It can set the long-term vision for aeronautics and the air transportation system. This role requires communication and interaction with the FAA, DHS, DoD, and other members of the Joint Planning and Development Office that is defining the nature of the Next Generation Air Transportation System and the research program necessary to make it a reality. The FAA, which must implement modifications to the system in an evolutionary manner, can develop its system roadmap in part by using the NASA end state.

Low-Priority R&T Challenges

Four R&T Challenges were not in the top 10. Three of the four (D12, smaller, lighter, and less expensive avionics; D13, more efficient certification processes; and D14, design, development, and upgrade processes for complex, software-intensive systems) had a significant impact on only one or two Strategic Objectives. For example, Challenge D14 is very relevant to the safety and reliability Strategic Objective but had only a minimal or modest impact on the other five Objectives.

The fourth R&T Challenge that did not make the top 10 was D11, secure, network-centric avionics architecture and systems. This Challenge has a significant effect on four of the Objectives, and it tied for the highest score in terms of national priority. However, it ranked low in terms of NASA priority because it scored worse than all of the top 10 Challenges in terms of alignment with the NASA mission and the availability of alternative sponsors.

Challenges D13 and D14 also scored in the top 10 in terms of national priority but not in terms of NASA priority. Challenge D13 is important because all new technologies must be certified before they can be put in service. D14 is important because many new systems will be software intensive. However, these Challenges scored low in terms of "Why NASA?" because (1) other organizations in government, industry, and academia are already working on relevant technologies and (2) NASA has relatively little infrastructure or expertise to contribute. However, because Challenges D11, D13, and D14 scored high as a national priority, some part of the national civil aeronautics effort should support relevant R&T.

INTELLIGENT AND AUTONOMOUS SYSTEMS, OPERATIONS AND DECISION MAKING, HUMAN INTEGRATED SYSTEMS, AND NETWORKING AND COMMUNICATIONS

Introduction

Aeronautics research encompasses much more than airframes and engines. For many years NASA has been in the forefront of discovering how human beings interface with aviation hardware. NASA has also been a leader in development of autonomous systems and communications interfaces. Accordingly, R&T Challenges in the Area of intelligent and autonomous systems, operations and decision making, human integrated systems, and networking and communications focus on issues associated with the air transportation system of today and tomorrow as a complex interactive system; issues associated with the performance of systems in individual aircraft are addressed in the preceding sections.

The Next Generation Air Transportation System (NGATS) Joint Planning and Development Office (JPDO) is striving to achieve eight key capabilities (NGATS JPDO, 2005, pp. 7-9):

- Network-enabled information access, which will give decision makers throughout the air transportation system quick access to the critical information they need in normal and emergency conditions.
- Performance-based services, which will maximize the performance of all categories of aircraft.
- Weather assimilated into decision making, which will take advantage of improved probabilistic weather information.
- Layered, adaptive security, which will be more efficient, more effective, and less intrusive.
- Broad-area precision navigation, which will allow pilots to make precision landings at airports that do not have control towers, radar, or an instrument landing system (ILS).
- Aircraft trajectory-based operations, which will include automatic, continuous analysis of trajectories to increase capacity and assure safe separation of aircraft.

- Equivalent visual operations, which will allow pilots and controllers to see the same picture, enabling controllers to delegate some tasks to pilots.
- Super-density operations, which will use advanced capabilities, including detection and avoidance of hazardous wake vortices, to enable closely spaced and converging approaches in the air as well as more efficient airport ground operations.

This study did not assess and does not necessarily endorse the above set of capabilities. However, many of the capabilities would be supported by R&T Challenges in this Area. These Challenges also encompass the basic and applied research necessary to establish a proper balance between automated and human-centric system configurations and operational concepts in the air transportation system. The scope of research in this Area includes new NASA R&T Thrusts as well as the expansion of existing technology programs. One Area of particular near-term interest is the incorporation of autonomous and semiautonomous aircraft into the national (and global) air transportation system.

The QFD process described in Chapter 2 was used to prioritize 20 R&T Challenges related to intelligent and autonomous systems, operations and decision making, human integrated systems, and networking and communications. Table 3-5 and Figure 3-7 show the results. The text that follows describes the 10 R&T Challenges that ranked highest in terms of NASA priority, the general characteristics of high- and low-priority Challenges, and the R&T Thrusts in this Area. Further details on all Challenges, including the rationale for scoring, are found in Appendix E.

As shown in Table 3-5, many of the Challenges in this Area ranked high because they would enhance the performance of the air transportation system as a whole, bringing about noteworthy improvements related to many of the air transportation system strategic objectives (capacity, safety and reliability, etc.). As shown Figure 3-7, the top 10 Challenges fall into three groups:

- R&T Challenge E1 stands alone, with a NASA priority score of 936.
- R&T Challenges E2 and E3 stand together with scores of 780 and 744.
- R&T Challenges E4 to E8c stand together with scores of 624 to 576.

The difference in scores and rankings of the R&T Challenges in each of the last two groups is not significant.

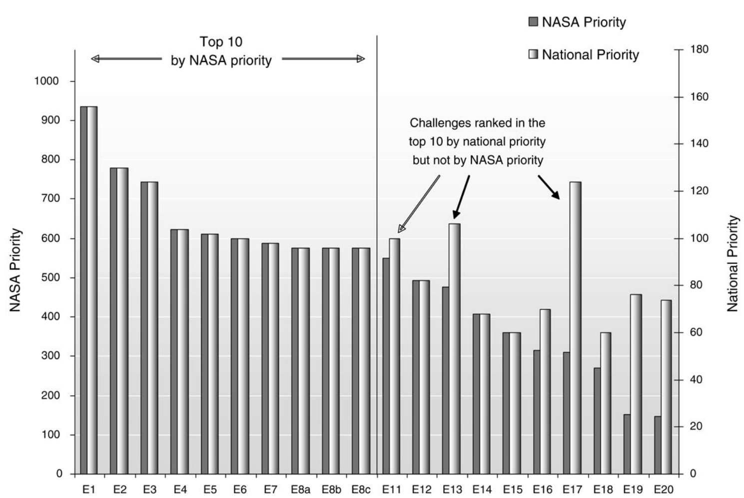

FIGURE 3-7 NASA and national priorities for Area E: intelligent and autonomous systems, operations and decision making, human integrated systems, and networking and communications

TABLE 3-5 Prioritization of R&T Challenges for Area E: Intelligent and Autonomous Systems, Operations and Decision Making, Human Integrated Systems, and Networking and Communications

		Strategic Objective							Why NASA?					
R&T Challenge	Weight	Capacity	Safety and Reliability	Efficiency and Performance	Energy and the Environment	Synergies with Security	Support to Space	National Priority	Supporting Infrastructure	Mission Alignment	Lack of Alternative Sponsors	Appropriate Level of Risk	Why NASA Composite Score	NASA Priority Score
		5		3		1			$^1/_4$ each					
E1	Methodologies, tools, and simulation and modeling capabilities to design and evaluate complex interactive systems	9	9	9	9	9	3	**156**	3	9	3	9	**6.0**	**936**
E2	New concepts and methods of separating, spacing, and sequencing aircraft	9	9	9	3	3	1	**130**	3	9	3	9	**6.0**	**780**
E3	Appropriate roles of humans and automated systems for separation assurance, including the feasibility and merits of highly automated separation assurance systems	9	9	9	1	3	1	**124**	3	9	3	9	**6.0**	**744**
E4	Affordable new sensors, system technologies, and procedures to improve the prediction and measurement of wake turbulence	9	9	3	1	1	1	**104**	3	9	3	9	**6.0**	**624**
E5	Interfaces that ensure effective information sharing and coordination among ground-based and airborne human and machine agents	3	9	9	1	9	3	**102**	3	9	3	9	**6.0**	**612**
E6	Vulnerability analysis as an integral element in the architecture design and simulations of the air transportation system	3	9	9	1	9	1	**100**	3	9	3	9	**6.0**	**600**
E7	Adaptive ATM techniques to minimize the impact of weather by taking better advantage of improved probabilistic forecasts	9	3	9	3	1	1	**98**	3	9	3	9	**6.0**	**588**
E8a	Transparent and collaborative decision support systems	3	9	9	1	3	3	**96**	3	9	3	9	**6.0**	**576**
E8b	Using operational and maintenance data to assess leading indicators of safety	3	9	9	1	3	3	**96**	3	9	3	9	**6.0**	**576**
E8c	Interfaces and procedures that support human operators in effective task and attention management	3	9	9	1	3	3	**96**	3	9	3	9	**6.0**	**576**
E11	Automated systems and dynamic strategies to facilitate allocation of airspace and airport resources	9	3	9	3	3	1	**100**	3	9	1	9	**5.5**	**550**
E12	Autonomous flight monitoring of manned and unmanned aircraft	3	9	3	1	9	1	**82**	3	9	3	9	**6.0**	**492**
E13	Feasibility of deploying an affordable broad-area, precision-navigation capability compatible with international standards	9	9	3	1	3	1	**106**	3	3	3	9	**4.5**	**477**
E14	Advanced spacecraft weather imagery and aircraft data for more accurate forecasts	3	3	9	3	1	1	**68**	3	9	3	9	**6.0**	**408**
E15	Technologies to enable refuse-to-crash and emergency autoland systems	1	9	1	1	3	1	**60**	3	9	3	9	**6.0**	**360**
E16	Appropriate metrics to facilitate analysis and design of the current and future air transportation system and operating concepts	3	3	9	3	3	1	**70**	3	9	3	3	**4.5**	**315**
E17	Change management techniques applicable to the U.S. air transportation system	9	9	9	1	3	1	**124**	1	3	3	3	**2.5**	**310**
E18	Certifiable information-sharing protocols that enable exchange of contextual information and coordination of intent and activity among automated systems	3	1	9	1	9	1	**60**	3	9	3	3	**4.5**	**270**
E19	Provably correct protocols for fault-tolerant aviation communications systems	3	9	3	1	3	1	**76**	3	3	1	1	**2.0**	**152**
E20	Comprehensive models and standards for designing and certifying aviation networking and communications systems	3	9	3	1	1	1	**74**	3	3	1	1	**2.0**	**148**

Top 10 R&T Challenges

E1 Methodologies, tools, and simulation and modeling capabilities to design and evaluate complex interactive systems

The U.S. air transportation system is a complex interactive system whose behavior is difficult to simulate with currently available models. Methodologies, tools, and simulation and modeling capabilities suited for the design and integration of complex interactive systems are needed to understand the air transportation system as an integrated, adaptive, distributed system that includes aircraft, ATM facilities, and airports, each with its own complex systems, all of which interact with one another, the environment, and human operators. Simulations and models for complex interactive systems are needed to accurately estimate system performance, to properly allocate resources, and to select appropriate design parameters. Additionally, the large number of possible future system designs requires models that can be reconfigured to model a wide range of design parameters.

E2 New concepts and methods of separating, spacing, and sequencing aircraft

Expected growth in the demand for air transportation will require efficient, denser en route and terminal area operations. This necessitates procedures that reduce minimum spacing requirements during all phases of flight and in all weather conditions, through an integrated approach that leverages a suite of emerging technologies such as required navigation performance and automatic dependent surveillance broadcast (ADS-B). The objective of this Challenge is to efficiently accommodate a large number and wide range of aircraft, including UAVs, through spacing and sequencing based on aircraft type and equipment rather than a common worst-case standard. Several concepts of operation should be systematically compared in terms of their technological, business, and human factors issues as well as their impact on capacity, safety, and the environment. This Challenge will study reduced separation operations within the context of existing ATM protocols and revolutionary paradigms that could significantly increase capacity, although the latter would involve a much more complicated transition process.

Integration of UAVs into the air transportation system will require procedures that can safely manage aircraft with diverse performance characteristics and highly automated onboard flight management systems (Sabatini, 2006). Safe, high-capacity operations in a complex future airspace environment will require fundamental research into alternative ATM paradigms such as simultaneous noninterfering operations (Xue and Atkins, 2006) in which general aviation, rotorcraft, and UAV traffic are threaded through airspace unused by commercial air traffic. As onboard automation and cooperative control algorithms are matured (McLain and Beard, 2005), UAV traffic might also be efficiently managed using formations of UAVs that are coordinated locally but treated as a single entity by air traffic controllers and pilots of nearby aircraft.

E3 Appropriate roles of humans and automated systems for separation assurance, including the feasibility and merits of highly automated separation assurance systems

Air traffic control is currently a labor-intensive process. FAA controllers—aided by radar, weather displays, and procedures—maintain traffic flow and assure separation by communicating instructions to aircraft in their sector of responsibility. Limitations to this traditional paradigm are, in some areas, constraining the capacity of the air transportation system. For example, the FAA required airlines serving the Chicago O Hare airport to reduce some of their flights during 2005 because of congestion-related delays. A recent study of en route sector congestion suggested that capacity could be increased by a factor of two or more while maintaining existing spacing, by developing new systems that merge human and computer decision making and automate time-critical separation assurance tasks (Andrews et al., 2005).

Initiatives to reduce aircraft separation by providing automated advisories to air traffic controllers and flight crews have not lived up to expectations, because of controller workload concerns, institutional resistance, and other factors. The advent of UAVs has caused additional concern because it may not be feasible for UAVs with human-in-the-loop collision avoidance schemes to act in time to prevent midair collisions. This has led to interest in determining whether automating aircraft separation, whereby the controller is neither in the loop nor responsible for separation, is feasible and desirable. However, changing the role of the controller from tactical separation to traffic flow management and trusting automated systems to manage the tactical separation of aircraft would require resolution of major human factors, safety, and institutional issues (Wickens et al., 1998; Woods and Hollnagel, 2006). Collisions could occur if a UAV fails to respond or the automated traffic separation system fails and if human intervention is not effective. This Challenge would determine the appropriate roles of humans and automated systems to assure separation in high-density airspace during nominal and off-nominal operations. As part of this challenge, NASA should assess the feasibility and merits of highly automated separation assurance systems.

E4 Affordable new sensors, system technologies, and procedures to improve the prediction and measurement of wake turbulence

Existing wake vortex separation standards reduce system capacity during takeoff and landing operations and instrument approaches. Encounters with a wake vortex are also a growing concern in en route Reduced Vertical Separation Minima (RVSM) airspace (Reynolds and Hansman, 2001).[12]

Current research by the FAA and NASA is focused on procedural enhancements that take advantage of wake transport by winds (Mundra, 2001). For example, the capacity of San Francisco International Airport is expected to improve by using this approach to enable arrivals on both closely spaced parallel runways during low-visibility weather. However, the relaxation of in-trail wake separation standards awaits improved measurement and prediction of wake behavior.

Existing sensors and models do not adequately characterize wake decay phenomena, especially at typical final approach altitudes. Improved sensors, including coherent pulsed lidars, capable of directly measuring wake rotational momentum, are needed to support phenomenological studies and enable more accurate predictions of wake magnitude and decay in various atmospheric conditions. Those predictions, combined with models of aircraft upset risk, should allow reduced wake separation standards without degrading safety.

R&T Challenge A10 will conduct research to improve techniques for predicting and measuring the formation, trajectory, and decay of vortices, including methods to accurately predict wingtip vortex formation and define changes in aircraft design to mitigate the strength of the vortices. This Challenge would complement that work by developing affordable new sensors, system technologies, and procedures to improve prediction and measurement of wake strength, location, motion, and aircraft upset risk in terminal and en route airspace. Together, Challenges A10 and E4 will enable safe flight with reduced in-trail wake separation.

E5 Interfaces that ensure effective information sharing and coordination among ground-based and airborne human and machine agents

The potential for sharing a wide range of information within the air transportation system raises additional questions about how multiple agents (pilots, controllers, other system users, and automated system elements) can coordinate and share information given their disparate viewpoints and contexts. For information sharing to be effective, information must be provided to the right agents, at the right time, and in a fashion that facilitates accurate interpretation regardless of the source of the information. Some of the shared information may be factual (e.g., aircraft position, speed, heading, altitude, and flight plan), while some of it may be less tangible (e.g., potential responses to disruptions). The information elements will also likely vary in their timeliness and accuracy, and access to some information will be restricted for security and business reasons. Developing appropriate interfaces (in terms of information-sharing protocols, as well as display and visualization technology) is a nontrivial challenge, because agents can be easily overwhelmed by too much information or by the need to translate and analyze the information relative to their own situation and goals (Woods et al., 2002). Interfaces for human agents, in particular, will need to include methods for visualizing and interpreting operational situations to facilitate effective judgments and decisions. In addition, information sharing and decision-making processes will often be conducted collaboratively by multiple agents. Therefore, they will require knowledge of both individual human cognition and of collaborative work among agents with potentially conflicting goals and different representations of the immediate situation (Brennan, 1998; Olson et al., 2001). Information-sharing protocols become exceptionally critical during crises, such as 9/11, when control of the national airspace was transferred to the military. Communications and decision-making protocols were fragmented. Research related to this Challenge must be coordinated with DoD and DHS to avoid a recurrence of such problems. The Challenge should also capitalize on technologies pioneered in the telecommunications industry that would facilitate the transfer of diverse information through dynamically reconfigured networks using thousands of disparate nodes.

E6 Vulnerability analysis as an integral element in the architecture design and simulations of the air transportation system

More than three-fourths of air transportation system delays are weather related (Meyer, 2005). Snow or thunderstorms at major hub airports often significantly reduce overall system capacity and efficiency. Abnormal en route winds cause unexpected peaking and depeaking at arrival gateways. En route convective weather causes disruptive and unpredictable rerouting, precipitating en route delays and reducing capacity and efficiency. Disruptions can also be caused by natural disasters (such as volcanoes, hurricanes, tornadoes, and wildfires), electronic attacks (such as power outages, hurricanes, GPS spoofing, spurious communication messages, and hacking into navigation aids), and physical attacks (such as destruction of control facilities and radars). The effects of these disruptions may be local, regional, or national. In all cases, system capacity and efficiency are directly affected, and, more important, the safety of the air transportation system may be compromised by an inadequate response.

Airlines use a variety of techniques to respond to such disruptions. Some reduce schedule to preposition aircraft for the recovery, when the weather abates; others try to fly their full schedule, hoping that the recovery will take care of itself.

[12]Reduced Vertical Separation Minima apply to the airspace from flight levels 290 to 410 (which is equivalent to altitudes of approximately 29,000 feet to 41,000 feet) and create twice as many usable flight levels, decreasing the vertical separation between aircraft from 2,000 feet to 1,000 feet. While increasing capacity, this also could exacerbate the effects of wake turbulence.

Assessing vulnerabilities and risks should be the first step in reducing the likelihood and consequences of unplanned system disruptions (Volpe, 2003, p. 4). System safety impacts of disruptions should be evaluated early in the development cycle of new ATM system architectures, operating concepts, and system components. An agile ATM design should include provisions to counter or recover from system disruptions, and the design of the overall air transportation system should be evaluated by research and simulation to develop both system design concepts and/or operational procedures. In addition, quantitative analyses should be used to assess the safety impact of system architecture options. This Challenge would introduce vulnerability analyses as an integral element in the architecture design and simulations of the air transportation system to reduce the likelihood that the system will experience major system disruptions, to mitigate the severity of specific system disruptions, and to facilitate recovery from system disruptions. The result would be an air transportation system that is self-diagnosing and self-healing.

E7 Adaptive ATM techniques to minimize the impact of weather by taking better advantage of improved probabilistic forecasts

Adaptive traffic flow management methods are needed to take advantage of recent improvements in automated aviation weather forecasts. About 70 percent of aviation delay is due to operationally significant weather, including thunderstorms, low ceilings and visibilities, high winds, and turbulence. Exploitation of weather data collected from ground sensors and satellites using advanced image processing and machine intelligence has enabled significant improvements in aviation weather forecasts. One- to two-hour storm motion products are now being routinely displayed in key airport and en route air traffic facilities and in airline dispatch centers. Included are automatically updated estimates of the forecast accuracy, expressed as a probability (Robinson et al., 2004). This information is beginning to be used by air traffic managers and dispatchers, but only manually (Wolfson et al., 2004).

Algorithms are needed that automatically translate the weather forecasts into actionable traffic flow recommendations, with the goal of fully incorporating the weather data into air traffic automation designs. A few examples of automation that translate probabilistic weather forecasts into traffic flow recommendations have been developed, and FAA air traffic managers have shown they can reduce delays. For example, the LaGuardia Airport traffic flow managers are using storm motion forecast tools, such as the Route Advisory Planning Tool, to automatically identify safe departure routes (Evans, 2006). However, many automation systems are not incorporating the new weather information into their designs. This Challenge would demonstrate the use of automated weather forecasts in making traffic flow decisions and determine where this capability is cost beneficial.

E8a Transparent and collaborative decision support systems

Air traffic operations are enhanced by effective decision support systems that assist pilots, controllers, traffic flow managers, and airline personnel in tasks such as routing, flight planning, scheduling, and traffic separation. These decision support systems contribute to safe and efficient operations by using technology to enhance human capabilities and collaborate with the operator, as opposed to fully automated systems, which use technology rather than an operator to perform tasks. Collaborative decision support systems are most effective when the operators understand the basis for and limitations in the system s reasoning process and can judge the appropriateness of system-generated recommendations. Similarly, the system s recommendations should take into account operators knowledge and intentions as well as the context in which they operate. Support for reciprocal information sharing and mutual understanding of intentions and actions—a process called grounding—is critical to avoid breakdowns in human–machine collaboration and overall system performance (Sorkin et al., 1988; Lee and Moray, 1994; Smith et al., 2001; McGuirl and Sarter, 2006). This Challenge will identify the type of information to be shared between human operators and automated decision support systems and develop candidate designs for these systems.

E8b Using operational and maintenance data to assess leading indicators of safety

Safety analysis is often a reactive, ad hoc process made difficult, in part, by the very high level of safety required of air transportation in the United States. Few unambiguous data points (accidents) are available for analysis, the number of data points continues to decrease because of the success of ongoing safety efforts, and accidents that do occur are increasingly the result of a complex chain of unlikely circumstances, each of them benign (Leiden et al., 2001). While human error is often cited as a major safety concern, successful human performance is also a major (and underreported) contributor to system safety. Thus, a particular concern for safety analysis is the human contribution to safety, especially when predicting the safety impact of dramatic changes to the role of human operators and increased reliance on automation. Likewise, safety analysis must consider individual aircraft as well as systemwide safety, which involves complex interactions among many agents. Using a common set of safety metrics (see R&T Challenge E16), this Challenge would develop methods both for monitoring the current system through ongoing analysis of operational and maintenance data and for predicting potential safety problems associated with proposed changes to the air transportation system.

E8c Interfaces and procedures that support human operators in effective task and attention management

The expected growth in air transportation demand will likely require operators to perform a wider range of tasks and to collaborate more closely with one another and with modern technologies. Pilots may begin to play a more active role in traffic separation or spacing and will need to coordinate their activities and intentions with other pilots and controllers. They will need to interact and exchange information, often interrupting each other and creating new tasks for one another. In general, more information will need to be distributed in a timely manner, task sets will increase, interruptions will become more likely, and the tolerance for delayed action or intervention will probably be reduced. It will be critical to ensure that operators are supported in properly scheduling and prioritizing their tasks, to improve attention management and avoid errors caused by unnecessary task switching, unnecessary interruptions, or inappropriate dismissals of demands (i.e., the failure to switch attention when appropriate and necessary) (Woods, 1995; McFarlane and Latorella, 2002; Ho et al., 2004).

High-Priority R&T Challenges and Their Associated Thrusts

Only one R&T Challenge in this Area (E1) had major relevance and impact on the energy and environment Strategic Objective. The other nine high-priority R&T Challenges in this Area each had major relevance and impact on at least two of the other three highly weighted strategic objectives (capacity, safety and reliability, and efficiency and performance).

In some cases, the R&T Challenges in this Area would have direct operational impact, for example, by developing new concepts and methods of separating, spacing, and sequencing aircraft to increase capacity and safety in all flight conditions (E2). In other cases, the benefits would be less direct, for example, by developing more capable methodologies, tools, and simulation and modeling capabilities to design and evaluate complex interactive systems (E1) and determining appropriate roles of humans and automated systems for separation assurance in high-density airspace during nominal and off-nominal operations (E3). Although the results of research in these areas would take longer to produce operational benefits, the research is essential, it is appropriate for NASA to include the research in a 10-year plan, and NASA involvement in the research is necessary to ensure that this research moves forward and can be readily applied to the air transportation system.

The ultimate objective of NASA s aeronautics research as it relates to intelligent and autonomous systems, operations and decision making, human integrated systems, and networking and communications is to provide the fundamental capabilities required for an adaptive and robust air transportation system that meets the nation s goals for economic growth, public well-being, and national security. Because the air transportation system is a complex interactive system, the linkages among its component systems are just as important as the component systems themselves. The committee identified four R&T Thrusts that describe threads of commonality among the Challenges in the intelligent and autonomous systems, operations and decision making, human integrated systems, and networking and communications Area:

- Decision making, negotiation, collaboration, information sharing, and allocation of airspace resources.
- Aircraft separation, spacing, and sequencing.
- Simulation, modeling, and analysis of complex, adaptive distributed systems.
- Wake and weather sensing, modeling and prediction, and other enabling air transportation technologies.

Each of these thrusts is discussed below. As shown in Figure 3-8, the first two Thrusts would lead directly to improvements in air transportation system operations, and the last two Thrusts would provide enabling technologies and capabilities that support the first two.

Decision making, negotiation, collaboration, information sharing, and allocation of airspace resources

Mechanisms must be constructed to facilitate and structure the interactions of all air transportation system components—businesses, organizations, individual humans, technologies—such that the emergent system performance is adequate. To do so requires foundational research into several topics, including the appropriate roles of automation; methods of supporting effective decision making and task management by individual humans, by automated systems, and by humans and automation working together; and information sharing, negotiation, and coordination within and between organizations. One outcome of these functions of particular importance to the design of the Next Generation Air Transportation System is allocation of airspace and airport resources, insofar as the method used to allocate these resources can determine how demand relates to capacity and whether airports and flights experience outcomes such as delays or denial of service. The following R&T Challenges are most closely related to this Thrust:

E5, Interfaces that ensure effective information sharing and coordination among ground-based and airborne human and machine agents.

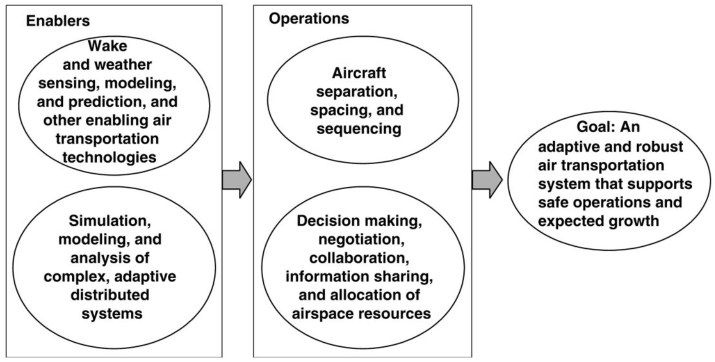

FIGURE 3-8 R&T Thrusts related to Area E: intelligent and autonomous systems, operations and decision making, human integrated systems, and networking and communications.

E8a, Transparent and collaborative decision support systems.

E8c, Interfaces and procedures that support human operators in effective task and attention management.

E11, Automated systems and dynamic strategies to facilitate allocation of airspace and airport resources.

E18, Certifiable information-sharing protocols that enable exchange of contextual information and coordination of intent and activity among automated systems.

Aircraft separation, spacing, and sequencing

The high-density airspace of the future will require effective management of aircraft separation, spacing, and sequencing in all flight conditions. The future air transportation system must develop improved models and novel operational concepts to support capacity growth and accommodate scheduled and unscheduled operations in airspace shared by manned and unmanned aircraft without compromising safety. Of particular importance to this research are separation assurance methods and understanding the appropriate roles of humans and automation in high-capacity airspace. Research in several R&T Challenges is needed to provide critical inputs, including accurate wake and weather forecasting as well as flight monitoring capabilities. The following Challenges are most closely related to this Thrust:

E2, New concepts and methods of separating, spacing, and sequencing aircraft.

E3, Appropriate roles of humans and automated systems for separation assurance, including the feasibility and merits of highly automated separation assurance systems.

Simulation, modeling, and analysis of complex, adaptive distributed systems

Design of the Next Generation Air Transportation System is a tremendous engineering challenge. This network of safety-critical, complex interactive systems will be vast in scope and involve multiple disparate organizations with separate objectives and capabilities. Examining the challenges facing this development, the committee found that individual technologies and systems will contribute to system performance only indirectly through their influence on how the larger system is collectively operated by the many user organizations; thus, system operations must also be a focus of research and development. Understanding the complexities of these operations requires new design tools and methodologies. Metrics are also important, because system performance metrics have a direct impact on the design of the system: Parameters that are not measured—or are measured incorrectly or incompletely—will not be fully considered or accounted for in the final design. Thus, it is critically important that the appropriate metrics be identified and incorporated into system analysis and design tools and processes. However, there is no comprehensive, widely held set of metrics to analyze and design the current and future air transportation system. Because many issues (e.g., economic, efficiency, safety, environment) must be addressed simultaneously, the problem cannot be decomposed into isolated examinations of capacity, safety, technology, human factors, etc. New simulation tools are needed with extensive predictive capabilities. Likewise, new analysis methods are required to integrate safety and vulnerability assessments into the design process. Coordinating all of these insights requires understanding of complex, adaptive distributed systems with the unique characteristics of air transportation, including the need to simulate and predict the behavior of radically different system configurations.

The following R&T Challenges are most closely related to this Thrust:

E1, Methodologies, tools, and simulation and modeling capabilities to design and evaluate complex interactive systems.

E6, Vulnerability analysis as an integral element in the architecture design and simulations of the air transportation system.

E8b, Using operational and maintenance data to assess leading indicators of safety.

E16, Appropriate metrics to facilitate analysis and design of the current and future air transportation system and operating concepts.

E17, Change management techniques applicable to the U.S. air transportation system.

E20, Comprehensive models and standards for designing and certifying aviation networking and communications systems.

Wake and weather sensing, modeling and prediction, and other enabling air transportation technologies

Several critical technologies warrant fundamental research by NASA for their likely value as enablers of many possible operational concepts, and because some are still in a nascent state. Of particular importance are the sensing, modeling, and prediction of aircraft wakes and hazardous weather. Other enabling technologies center on the creation of enhanced automation capabilities for safety (e.g., "refuse-to-crash") and for capacity (e.g., agents for negotiating resource allocation) beyond those that the research community currently knows how to develop and certify as robust in a wide range of conditions. Additional technologies focus on further enhancements to the communication and navigation needs of air traffic management functions. The following R&T Challenges are most closely related to this Thrust:

E4, Affordable new sensors, system technologies, and procedures to improve the prediction and measurement of wake turbulence.

E7, Adaptive ATM techniques to minimize the impact of weather by taking better advantage of improved probabilistic forecasts.

E12, Autonomous flight monitoring of manned and unmanned aircraft.

E13, Feasibility of deploying an affordable broad-area, precision-navigation capability compatible with international standards.

E14, Advanced spacecraft weather imagery and aircraft data for more accurate forecasts.

E15, Technologies to enable refuse-to-crash and emergency autoland systems.

E19, Provably correct protocols for fault-tolerant aviation communications systems.

Low-Priority R&T Challenges

Seven of the 10 R&T Challenges that did not rank in the top 10 by NASA priority also ranked low in national priority. Which is to say, they had substantial impact on only one of the highly weighted strategic objectives (capacity, safety and reliability, efficiency and performance, or energy and the environment). The other three R&T Challenges (E11, E13, and E17) would have substantial impact on two of the highly weighted strategic objectives, but they ranked low in terms of NASA priority because of low Why NASA? scores. Because these Challenges rank high in national priority, it is important that some part of the national civil aeronautics R&T effort (by NASA, other government agencies, industry, or academia) support work to overcome them.

E17 Change management techniques applicable to the U.S. air transportation system

The current ATM airspace architecture and associated procedures are antiquated and so reliant on interim fixes that there is significant resistance to additional changes. A novel and consistent approach is needed to manage changes to the ATM system and to overcome barriers and organizational inertia within the FAA and other stakeholders. The FAA should support research related to this Challenge, though it may take external pressure (e.g., from the Office of Management and Budget, the Government Accountability Office, and the White House) to prompt action. It may be appropriate for NASA to also conduct research related to this Challenge, but NASA would first need to increase its relevant capabilities.

E11 Automated systems and dynamic strategies to facilitate allocation of airspace and airport resources

The current allocation of airspace and airport resources (e.g., airport departure and arrival slots) at major airports is heavily biased toward airline operations. The competition for airspace and airport resources will be exacerbated by growth in commercial and private air travel, including the introduction of very light jets. Future air transportation systems would benefit from built-in automatic response systems driven by software agents that quickly negotiate and make decisions regarding, for example, real-time allocation of airspace and landing slots among aircraft with diverse size and performance characteristics, while considering the needs of all stakeholders, air transportation system efficiency, and energy conservation (Cramton et al., 2002). This Challenge ranked low in NASA priority because the FAA already is funding some related research and is best suited to address this Challenge.

E13 Feasibility of deploying an affordable broad-area, precision-navigation capability compatible with international standards

Many small airports cannot operate when visibility is restricted because they do not have the equipment (e.g., a Category I, Category II, or Category III instrument landing system) necessary for a safe approach and landing.[13] The number of ILS frequencies available in large metropolitan areas, where multiple runways require precision approach and landing capabilities, is limited. Increased access to these airports and runways would increase efficiency significantly, particularly for some segments of the aviation industry (e.g., feeder airlines, business aircraft, and air taxis). While satellite navigation systems are currently deployed by the United States and others, they do not provide sufficient coverage, accuracy, and reliability for aviation requirements to replace or substitute for ground-based aids, particularly as regards precision landing guidance provided by ILS (Shively and Hsaio, 2005). The objective here is to design, develop, and deploy a space-based navigation system augmentation that complements GPS, Galileo, and the Global Navigation Satellite System (GLONASS), so that guidance equivalent to Category IIIc ILS is universally available and no additional ground-based capability (e.g., pseudolites) needs to be installed. Deployment of this capability would open up any airport or temporary landing area for all-weather operations with no need for expensive and time-consuming construction; facilitate reconfiguration of approach paths; and improve safety. It would allow many existing runways and small airports not equipped with ILS to operate in low visibility conditions and would support emergency operations and homeland security. It would have the added benefit of allowing the FAA to remove thousands of existing en route and terminal navigation aids, such as very high frequency (VHF) omnidirectional range (VOR) equipment, distance measurement equipment (DME), tactical air navigation (TACAN) systems, ILSs, and nondirectional beacons (NDB). Decommissioning these systems would eliminate associated maintenance and operating costs. This Challenge ranked low in NASA priority primarily because the feasibility of deploying an affordable, broad-area precision navigation capability will be determined by technical, economic, and regulatory issues. The technical feasibility issues are well aligned with NASA s aeronautics mission, but economic feasibility issues are better handled by industry, and regulatory feasibility issues are better handled by the FAA.

[13]An ILS is a ground-based precision approach system that provides course and altitude guidance to pilots as they prepare to land. ILS systems are rated according to their capabilities:

A Category I system can provide guidance regarding course and glide slope down to an altitude of 200 feet with a runway visual range of not less than 1,800 (or 2,400 feet depending on runway lighting and configuration).

A Category II system can provide guidance regarding course and glide slope down to an altitude of 100 feet with a runway visual range of not less than 1,200 feet.

A Category IIIa system can provide guidance regarding course and glide slope all the way to touchdown as long as the pilot has some external visual reference during the final phase of landing and the runway visual range is not less than 700 feet.

A Category IIIb system can provide guidance regarding course and glide slope all the way to touchdown even without any external visual references, as long as the runway visual range is not less than 150 feet (for taxi operations after landing).

A Category IIIc system can provide guidance regarding course and glide slope all the way to touchdown and during taxi operations without any external visual references and with zero visibility.

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4

Common Themes and Key Barriers

COMMON THEMES

Chapter 3 describes R&T Thrusts, which are threads of commonality among the R&T Challenges identified by each panel within its own R&T Area. The steering committee also identified threads of commonality among the R&T Thrusts and the R&T Challenges from different R&T Areas and called them Common Themes:

- Physics-based analysis tools
- Multidisciplinary design tools
- Advanced configurations
- Intelligent and adaptive systems
- Complex interactive systems

These Themes are not an end in themselves; they are a means to an end. Each Theme describes enabling approaches that will contribute to overcoming multiple Challenges. Exploiting the synergies identified in each Common Theme will enable NASA s aeronautics program to make the most efficient use of available resources.

Physics-Based Analysis Tools

Description

Physics-based analysis tools attempt to predict the behavior of physical and/or chemical phenomena by solving the fundamental governing conservation, constitutive, and state equations together with appropriate closure equations based on first-principle physical models. In other words, "physics-based" refers to the general use of scientific principles in place of empirical data. The tools can be hierarchal in space and time, and the lowest order model (e.g., zero-dimensional steady state and two-dimensional unsteady state) that predicts a phenomenon to the accuracy desired should be employed. This Theme also includes models derived from other branches of science, such as chemistry, biology, materials science, computer and information science, and cognitive science, though many are not strictly physics-based. For complex problems such as three-dimensional, unsteady, heterogeneous flows, computational simulations that provide numerical solutions must generally be used.

Background

This Theme is particularly applicable to three R&T Areas examined in this study: aerodynamics and aeroacoustics, propulsion and power, and materials and structures. Physics-based analysis tools offer the opportunity to decrease significantly the use of empirical approaches in aeronautics R&T. Empiricism, as defined here, refers to the generation of information through cut-and-try experimentation and testing. It is not inherently bad as long as the results are integrated with models, lead to knowledge and understanding, and are not widely extrapolated beyond the ranges of the test parameters. To a great degree, enlightened empiricism was responsible for many of the aeronautical advances of the previous century. Empiricism, however, can be expensive and time consuming and may not lead to a fundamental understanding of phenomena. From a national perspective, empirical modeling and design can be an inefficient use of resources and may lead to compromised, nonoptimal designs that rely on unnecessarily large design margins.

An important benefit of advances in physics-based analysis tools is the new technology and systems frontiers they open. New concepts often emerge from a greater understanding of the underlying physics offered by new analytical capabilities. In these cases, experimentation might never lead to the level of insight offered by even relatively simplistic physics-based tools. An example of this is sonic-boom mitigation technology. It is highly unlikely that any practical amount of experimentation will lead to a design for a low-sonic-boom aircraft. The development of linear and nonlinear physics-based analysis tools is necessary to mature this technology.

With advances in computational speed, computing power, and the affordability of digital processors in the last two decades, aeronautics researchers in industry, academia, and the government have turned increasingly to computational simulations to model complex physical and chemical phenomena. Industry is motivated by the possibility of using computational simulations to reduce the cost and time of product development, while increasing product reliability. Academic and government researchers also value the ability to attack more complex problems. These computational simulations generally employ a number of physics-based models within the governing conservation and state equations. Examples include models that describe droplet behavior and interactions, particulate matter formation, turbulence, turbulence–chemistry interactions, boundary-layer growth and transition, fracture, crack propagation, and material phase boundaries. A lack of fundamental understanding often requires these models to contain adjustable parameters that are grossly calibrated to empirical data sets. These data sets are often incomplete, which means that untested assumptions must be incorporated in the models. The computational simulations are generally not validated in spatial detail except for comparison of code predictions to input and output measurements. Additionally, the adjustable parameters are tweaked to match predictions with measurements. It is not uncommon to find that the codes do not extrapolate well when the design space changes considerably, prompting more tweaking of the adjustable parameters. Also, when results are presented, details are usually omitted in connection with the use of boundary conditions or how adjustable parameters were set, making it harder for independent researchers to reproduce the results. Thus to a large extent, empiricism has transitioned from the physical to the computational realm, but it persists. Nevertheless, within their applicable ranges, computational simulations have enabled technical progress, as witnessed by the state of aeronautics today. Unfortunately, limits on the use of simulations are often not well understood.

Suggested approach

NASA and its academic and industrial partners can make very significant contributions in developing and validating physics-based analysis tools. These are readily assimilated by industry into their proprietary product design codes. NASA, industry, and academia can jointly participate in research into physics-based analysis tools because it is fundamental in nature, publishable, and sharable. This research will take time to mature, yet advances can readily be translated into practice as they occur. Furthermore, given the budget- and schedule-driven nature of the aerospace business, this is the type of work that industry can no longer afford to pursue. Developing physics-based tools whose accuracy and range of applicability limits are well established is a lengthy, iterative process. Validation requires well-designed experiments to elucidate the underlying physics as well as experimental facilities of appropriate scale and advanced, nonperturbing diagnostics to perform detailed, spatially and temporally resolved measurement of parameters.

Benefits of synergy

Advances in physics-based analysis tools would help address R&T Challenges in all of the R&T Areas. For example, turbulence modeling is a key element in the accurate prediction of mixing, which is very important in many aspects of aerodynamics (A2), aeroacoustics (A4a, B1a), and combustion processes (B1b). Accurate predictions of flow separation are a prerequisite to the successful design of both nonreacting (A2, A4a, A4b) and reacting (B1a, B1b, B5, B8) flow devices. Mathematical models of material properties and reactions are essential for structural response (A4a, C4, C10). Droplet–droplet and droplet–flow interactions are important processes in predicting both icing (A6) and combustion behavior (B1b, B8, B10). Modeling flow–structure interactions accurately is an important element of aeroelasticity and noise generation (A4a, B1a, C5, C6b). The development of higher-temperature alloys is key to improving propulsion system fuel efficiency (B4, C6a). Many of the computational science issues associated with large, complex computational simulations, such as automated grid generation, parallelizing codes, and error propagation analyses, are common elements across several R&T Areas.

Relevant R&T Challenges

The following R&T Challenges would benefit significantly from using physics-based analysis tools: A1, B1a, B1b, E1, A2, E2, D3, A4a, A4b, B4, C4, D4, E4, B5, C5, A6, B6a, C6a, C6b, A7b, B8, A9, B10, and C10.

Multidisciplinary Design Tools

Description

Discipline-specific design tools, including optimization and inverse design, have improved the performance of airfoils, wings, structures, control systems, and propulsion systems for many years, and they are now critical parts of the design process. The next step in the design of more complex systems involves more than just combining these disciplinary tools or gluing together discipline-specific analyses and optimization. New multidisciplinary tools are needed to integrate high-fidelity analyses with efficient design methods and to accommodate uncertainty, multiple objectives, and large-scale systems. Research in efficient methods for including large numbers of design variables (e.g., adjoint methods, multifidelity models, and surrogate models), probabilistic design methods, and tools for distributed, complex systems is particularly important to the development of future aeronautical systems.

Background

Methods for simulation-based multidisciplinary design and optimization (MDO) are at the very core of a philosophy that moves away from empirical methods that have proven to be expensive and often have not met expectations in exploring the aeronautical design space. MDO processes bring together people, analytical tools, experimentation, and information to design complex structural components and systems.

The design of aeronautical systems requires a system-level, multidisciplinary approach to assessing potential costs, benefits, and risks. Design tools that couple a small number of disciplines in a restricted design space have reached a level of maturity and fidelity that make them important parts of the design process. For example, aeroelastic design tools are now within reach that couple computational fluid dynamics, multibody dynamics, and finite-element analyses for full aircraft configurations. In structural designs where the topology or outer mold lines are defined, analytical methods such as the structural finite-element technique, coupled with similar analytical tools for load assessment, promise success. More recently, high-fidelity multidisciplinary design tools have begun to incorporate a broader range of disciplines and are starting to be used earlier in the design process.

However, for designs with a multiplicity of topologies, some of which are not well defined, and for problems where a large number of design parameters and constraints must be considered in the early stages of the design process, the multidisciplinary design process is still underdeveloped. One of the major limitations of past efforts to create MDO tools has been a low level of fidelity, driven by a lack of physics-based models that are efficient and appropriate for system-level design. In addition, MDO tools have often lacked flexibility and have been developed and applied for very specific applications.

Suggested approach

Significant new developments are required in both the design strategies and the embedded tools that constitute the multidisciplinary design process. Key issues associated with next-generation multidisciplinary design tools include fidelity, computational efficiency, and the ability to handle uncertainty.

Efficiency and effectiveness continue to be a problem, particularly in large-dimensionality problems and multimodal or disjointed search spaces. Most current approaches to design are ill-equipped to deal with the vast amounts of data associated with the design process. High numerical efficiency is paramount for multidisciplinary design tools, and alternative paradigms that take advantage of a new generation of parallel computational hardware must be sought. Furthermore, not all methods are ideal for all problems. The goal of this Theme is not to generate one perfect, all-encompassing algorithm but to use the most efficient and effective method or combination of methods for each problem. Proper algorithm selection in itself is an important research topic.

Uncertainty modeling in a data-lean environment, which is often the case with new concepts, continues to be an issue, particularly in situations where uncertainty distributions do not conform to standard forms or where components or elements exhibit discrete behavior. The propagation of uncertainty in complex and highly coupled multidisciplinary systems needs to be modeled, and tools for design and optimization in a nondeterministic environment continue to be computationally intractable, especially when applied to design problems involving a large number of nondeterministic variables, parameters, and design constraints.

Methods for distributed design (where the design team is geographically dispersed) and for the design of large-scale distributed systems have achieved some success but have been restricted to special types of problems. Continued development of more general, scalable approaches to this problem is also critical for the design of complex systems.

The practical resolution of these issues will require fundamental research efforts in the development of design-oriented, physics-based models; new design methodologies that can seamlessly manage models of multiple fidelities for the various components of the system; methods to increase the computational efficiency of tools; methods to handle complex interactions with high accuracy; and methods to manage uncertainty in the design process.

Benefits of synergy

Multidisciplinary design processes develop synergistic benefits by integrating people, analytical tools, experimentation, and information to design complex components and systems. Their importance is reflected in the relevant R&T Challenges listed below.

Relevant R&T Challenges

Many Challenges in each R&T Area rely on improved multidisciplinary design tools. These include Challenges A1, A2, A3, A4a, B1a, B1b, B4, B8, C6b, D3, and D4. In addition, many R&T Challenges identify multidisciplinary design tools and design under uncertainty as core technologies, including A11, C3, D2, and E1.

Advanced Configurations

Description

Advanced configurations embody innovative, outside-the-box approaches to better meet the strategic objectives outlined in this report. They serve as technologies in themselves when they represent advancements in system-level definitions beyond those possible with conventional design tools, methods, and expertise. Examples of advanced configuration technologies include revolutionary aircraft concepts and advanced structural designs.

Background

Integration of innovative technologies into advanced configurations has long been a part of U.S. aeronautical development. For example, the Bell X-1A demonstrated supersonic flight, thus pushing the envelope beyond what was once thought to be an impassable barrier. Other advanced system configurations, such as the X-15, X-29, and X-35, have demonstrated multiple advanced technologies. Other examples, such as the Gossamer-Condor, Voyager, and Helios aircraft, demonstrated advanced vehicle configurations that were groundbreaking innovations and went beyond validated analytical methodologies.

Suggested approach

Creativity and good ideas have been at the center of revolutionary advances in aeronautics. One of NASA s roles is to foster the implementation of innovative solutions to challenging technological barriers. The development of innovative concepts needs to include freedom to innovate as well as physics and engineering checks. It is implicit that available design tools (from component-level, physics-based tools to MDO models) and empirical knowledge will be used to screen concepts before new tools and models are created.

Innovation is not possible, however, without tolerance for failure. The progression from technology identification, maturation, and demonstration to implementation is rarely linear. Advanced configurations, regardless of "success," form the basis for validating component-level and system-level physics-based models and MDO approaches. For example, the development programs for the SR-71 and NASA s XV-15 tilt-rotor had technology problems, but both produced functional aircraft. Even today, technical gaps persist in modeling the high-speed flight aerodynamics and combustion processes of the SR-71. However, by having a good balance between innovation, tolerance of failure, sound technical knowledge and judgment, and engineering analysis, the SR-71 came to fruition and became the fastest and highest-flying production aircraft ever built. The XV-15 demonstrated V/STOL capabilities, and programs such as the V-22 Osprey and the Bell/Agusta BA609 civil tilt-rotor aircraft have greatly benefited from and advanced the concepts demonstrated by the XV-15. Design and testing of advanced configurations should continue to have an important presence in civil aeronautics R&T.

Another aspect of innovation on advanced configurations is the process of integration itself. Oftentimes, outside-the-box thinking is needed to seamlessly integrate technologies that have been optimized individually but not yet integrated into a system. How to best integrate different technologies is a topic common to many R&T Challenges.

Benefits of synergy

Many synergies arise when developing advanced system configurations that integrate diverse technologies. For example, there is a direct synergy between advances in variable-cycle engines and the development of supersonic aircraft. Similarly, research on sonic boom mitigation is integral to the design of engines and propulsion systems for supersonic civil aircraft. In addition, for hypersonic vehicles (e.g., scramjet), the propulsion system cannot be designed separately from the rest of the vehicle. In this case, technologies that support the engine and vehicle often mature hand-in-hand as the systems are integrated. Many advanced configurations would also benefit from new sets of active control techniques and smart components (engines, materials, structures) that can self-diagnose and repair. Moreover, from the operational point of view, advanced (and even current) configurations benefit from a change in paradigm in the way that guidance, control, and real-time weather information is shared and used by pilots, controllers, and air traffic managers.

Relevant R&T Challenges

The following R&T Challenges are closely related to advanced configurations: A1, C1, C2, E2, A3, B3, D3, A4a, C4, D4, B5, C5, D5, B6a, B6b, C6a, E6, A7a, E7, B8, C8, A9, A10, B9, B10, and C10.

Intelligent and Adaptive Systems

Description

When an emerging detailed knowledge of physical phenomena is combined with the development of miniaturized sensors, compact actuators, and powerful computational capabilities, the potential exists to develop intelligent and adaptive systems with significantly improved performance and robustness. This Common Theme encompasses aircraft-level R&T Challenges aimed at sensing the operational environment, actively responding to that environment, and learning from the resulting interactions. Examples include (1) flow control techniques for improving aerodynamic performance, reducing noise, increasing maneuverability, and making aircraft robust to atmospheric disturbances and adverse weather conditions and (2) methods for improving the interaction of humans with aircraft systems. This Theme also involves technologies aiming at development of smart engines and mechanical power systems, adaptive materials and morphing structures, load suppression, and vibration and aeromechanical stability control.

The development of innovative classes of aircraft and complex systems will be facilitated by techniques to overcome the design and operational constraints and the physical limits of current systems. Each of the R&T Challenges related to this Theme involves the measurement of physical characteristics of a system in an effort to develop responsive and flexible schemes to improve system performance, robustness, efficiency, and safety.

Background

While some technologies encompassed by this Theme are relatively immature, significant performance improvements can be expected through development and execution of a coordinated research plan. Many promising flow control techniques have already been developed, such as microfluidic injectors, piezoelectric synthetic jets, voice-coil actuators, dielectric barrier discharges, and surface plasma discharges. These techniques have shown promise in the laboratory with limited, scaled flight testing. Adaptive materials with the ability to radically change their properties are also being explored, with the goal of affecting load-carrying capability and allowing large variations in wing area or shape. In the past 2 years, prototypes from DARPA s Morphing Aircraft Structures program have been demonstrated at transonic speeds in the Transonic Dynamics Tunnel at NASA Langley. Significant advancements in sensing techniques have also been realized with respect to miniaturization, frequency response, and allowable environmental operating conditions. Techniques currently exist to measure both surface and in-stream properties useful for adaptive control techniques. Finally, basic control techniques are available, but research is needed in the flight control laws for systems with a large number of highly distributed sensors and actuators, nonlinear adaptive control techniques, and adaptive techniques compatible with the failure of distributed sensors and actuators.

Suggested approach

To fully realize the benefits of the research within this Theme, cross-disciplinary teams will be required. Coordination across the R&T Challenges should be pursued to leverage promising developments in overlapping technologies. Efforts aimed at improving aircraft performance will require people with detailed knowledge in the following areas:

- The fundamental physical processes being controlled.
- Novel actuator designs, including material and structural response and electronics.
- Innovative sensing techniques.
- Information technology.
- Control theory.

The cross-disciplinary teams should interact frequently with designers and operators of current systems to clearly understand evolving constraints of existing systems. In addition, control of one parameter may have unexpected consequences for other parameters. These trade-offs must be identified and understood before they can be addressed.

Benefits of synergy

Integration of the R&T Challenges within the Common Theme on intelligent and adaptive systems would facilitate the cross-pollination of ideas and techniques. For example, flow control actuators developed for improving external aerodynamics may well find application in propulsion systems, while adaptive materials and structures developed for morphing aircraft may find application in noise reduction efforts. With this research conducted as an integrated Theme, rapid and effective implementation of advancements could be realized across historically disparate domains.

Synergies also exist between this Theme (which focuses on aircraft R&T) and the Common Theme on complex interactive systems (which focuses on the air transportation system as a whole). Intelligent and adaptive systems developed for use on aircraft potentially provide information useful in the operation of larger, more complex air transportation systems. For example, sensors incorporated into an aircraft to detect icing may well provide information useful to the ATM system.

Relevant R&T Challenges

The following R&T Challenges are closely related to intelligent and adaptive systems: E1, C1, A2, C2, D2, E2, B3, D3, E3, A4a, D4, E4, C5, D5, A6, C6b, D6, E6, A7b, D8, E8b, E8c, D9, and C10.

Complex Interactive Systems

Description

As noted in Chapter 1, as used in this report, a complex interactive system (also known as a system of systems) refers to an adaptive system consisting of a large, widespread collection or network of independent systems functioning together to achieve a common purpose. Complex interactive systems are distinguished from large, monolithic systems by the independent functioning of their components, which provides freedom for existing components to evolve and new components to emerge independent of a central configuration control authority. Complex interactive systems also tend to be distributed over a large geographic area and require effective communications and coordination protocols for the various components to interact efficiently (Maier, 2006).

To achieve the Strategic Objectives, the air transportation system must be understood as a complex interactive system, because its performance emerges from collective interactions among many independent systems and organizations, including aircraft of many different types, capabilities, and missions; pilots; air traffic controllers and air traffic flow managers; communication, navigation, and surveillance systems; airline operation control centers; manufacturers; labor organizations; and air carriers of many different sizes, capabilities, and operating philosophies. All of these "components" of the air transportation system loosely operate under a set of operating agreements, rules, regulations, and communications protocols established by international, national, and local government and nongovernmental organizations.

Background

As aeronautic systems become more complex, the following systems issues become more critical and more difficult to examine:

- When system performance is itself a complex, nondeterministic phenomenon emerging from the interaction of independent system components with stochastic behaviors, it may not be feasible to develop an analytical model of the entire system, making it difficult to describe, explain, and predict the system performance resulting from changes to any system component.
- Correspondingly, when a change to system behavior is desired, translation of this system-level representation into specific requirements for components can be difficult.
- Unlike centrally organized systems, which may be decomposed according to a hierarchy of control, decomposing the system model into design-manageable elements may be impossible when many different components interact in many different ways.
- The components behaviors (especially human behaviors) will often be context dependent, especially when they are attempting to meet several competing objectives. Thus, a small change in one part of the system may change the operating context of several components, generating broader, unanticipated effects.
- The types of behaviors that can significantly impact system performance include not only the physical functioning of technologies but also the cognitive behaviors of humans in the systems; social and organizational dynamics; and economic dynamics.
- Complex interactive systems are typically collaborative—that is, they allow component systems to more or less voluntarily collaborate to fulfill agreed-upon central purposes. Agreements among the central players on service provision and rejection provide a primary enforcement mechanism to maintain standards.
- The linkages between components are typically created through communication and coordination protocols rather than mechanical linkages or command structures.

Looking specifically at the air transportation system, much of its structure has evolved over time, with each independent entity finding methods of operation that satisfy its own goals as much as possible within the overall constraints that are imposed upon them. Human–machine and machine–machine interfaces are often created after the development of the technologies and operating concepts, sometimes leading to problems when interface design is unduly difficult or expensive. Aircraft have been developed to meet market demands without full consideration of overall impact on the system of variant performance characteristics, which may reduce system capacity and efficiency. System models typically examine isolated effects or components within the system, and few models attempt to examine a large range of complex, interactive system effects, especially those involving nondeterministic behaviors. Additionally, current system models are not easily reconfigured or adaptable to real-time analysis.

Suggested approaches

Key to analyzing a complex interactive system such as the air transportation system is developing a suite of interacting models with comprehensive simulation and analysis capabilities. Such an interactive system of models should be capable of (1) assessing impacts locally within system components as well as globally across the system and (2) introducing new systems, operating procedures, and protocols for information transfer, communication, coordination, and collaboration. In addition, models suited to complex interactive systems are needed early in the conception and design of any technology intended to function within such a system, including systems intended to support human activity. This process will be facilitated by explicitly representing the anticipated contributions of the technology to the larger system.

The need for clear communication and coordination protocols within the system is another critical design consideration. System designs should also consider the need for collaborative decision making, the relative roles and authority of the components (including organizational structures and the role of technologies in mediating human interactions), and their information needs.

Benefits of synergy

The ability to analyze complex interactive systems is relevant to many R&T Areas, and methods of modeling and analyzing such systems can be broadly applicable. Redesigning the air transportation system will be difficult, but the ability to accurately and efficiently model it as a complex interactive system will help reduce program risk and allow coordinating design efforts across multiple agencies.

Relevant R&T Challenges

The following R&T Challenges are closely related to complex interactive systems: C1, E1, D2, E2, B3, C3, E3, E4, E6, A7b, E8a, E8b, E5, and D10.

KEY BARRIERS

The steering committee identified two key barriers to achieving the six Strategic Objectives that should guide civil aeronautics R&T: (1) certification and (2) change management, internal and external. If these barriers are not addressed, the Strategic Objectives will not be accomplished, even if individual R&T Challenges are successfully overcome. Although these barriers may not appear to be explicitly part of NASA s mission, if they are considered from the earliest stages of research, the civil aeronautics community will be more likely to use the results of NASA R&T in developing operational products and procedures. Furthermore, the barriers have technical aspects, which the R&T Challenges will address.

Certification

Certification is the demonstration of a design s compliance with regulations. For example, before it can be operated by U.S. airlines, a new aircraft must be shown to comply with U.S. federal aviation regulations. As systems become more complex and nondeterministic, methods to certify new technologies become more difficult to validate. Core research in methods and models for assessing the performance of large-scale systems, human-interactive systems, nondeterministic systems, and complex, software-intensive systems, including safety and reliability in all relevant operating conditions, is essential for NASA, because such research is currently beyond the capabilities of regulators such as the FAA. The ultimate utility of this research will be significantly enhanced through early and consistent coordination of technology maturation with the FAA and other organizations responsible for certification of operational systems. Furthermore, this research would be facilitated by collaboration with other organizations involved in advanced software development methods.

Certification can also be a major barrier to the ultimate implementation of new technologies and operating concepts. In some cases, such as low-cost avionics for general aviation, the cost of certification can be several times greater than the cost of developing and manufacturing the product itself. Furthermore, relying on empirical testing to demonstrate compliance with certification standards may not be feasible for large-scale systems (including complex, software-intensive systems and air traffic operating concepts) and human-in-the-loop behaviors, which are not the same in different operating contexts; in these cases, certification will be substantially aided by the use of design tools and design processes developed to mitigate concerns about design validity, safety, and reliability. Certification issues can be show-stoppers if not addressed early in the R&T process. Thus, NASA should address the following concerns in its aeronautics R&T program:

- Systematic documentation and publication of model and design assumptions from the earliest stage of R&T development, to aid in a technology s ultimate certification.
- Ongoing iterative validation of models and design tools—and their specifications—during their development, and verification of models and design tools relative to their specifications.
- Generation of databases and models from empirical data to provide a basis for validation and certification.
- Establishment of community-accepted metrics, criteria, and methods for validation and certification.

Change Management, Internal and External

The air transportation system includes large organizations with long-standing institutional cultures and business concerns that are impacted by—and sometimes resist—the introduction of new technologies. These organizations must be motivated to participate in new operating concepts and to accept the risk of change to improve performance. Changing an interactive system as complex as the air transportation system is difficult because it involves changing a large number of individual elements, including equipment of many different kinds, personnel training, institutional organization, and business models. Additionally, the end state of the air transportation system remains undefined, so R&T should create and maintain the flexibility to steer the system in any of several different directions. This requires interdisciplinary applications of large-scale systems engineering, organization design, economics, and financial analysis, an approach which in some ways is beyond the current state of knowledge. Even so, improved change management techniques are vital to a cost-effective, noncontentious, and safe transition to the air transportation system of the future.

Change management within the federal government is particularly important because of the major impact that federal agencies, regulations, and funding have on the operation of the air transportation system and the development of new aeronautical technologies. In addition, change management within the federal government is particularly difficult because of the complex internal organization of the federal government, with multiple independent agencies, competing national priorities, and political factors that are beyond the control of any one person or agency. One way to facilitate change in the midst of such complexity is to establish strong, focused leadership that establishes a public/private process for change that defines air transportation as a national priority, produces a widely endorsed long-term vision of the air transportation system, and coordinates action by interested organizations. The process should be carefully structured to accommodate the increasing complexity of the air transportation system, competing national and organizational priorities, and fiscal limitations. The process should produce validated R&T requirements, a clear understanding of government and industry roles, and a plan to implement new technologies, operational concepts, and system architectures (NRC, 2003). The establishment of the Next Generation Air Transportation System (NGATS) Joint Planning and Development Office (JPDO) is an example of federal efforts to change interagency relationships to improve change management in civil aviation.

The issues related to change management transcend NASA s role as a single agency. The federal government should continue to support the work of the JPDO while conducting a high-level review of organizational options for ensuring U.S. leadership in civil aeronautics.[1]

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[1] A more detailed assessment of the management and organizational issues associated with NASA aeronautics R&T appears in another recent report, *Aeronautics Innovation: NASA s Challenges and Opportunities* (NRC, 2006).

5

Findings and Recommendations

PRINCIPAL FINDINGS

R&T Challenges

The top 10 R&T Challenges for each R&T Area are listed in Table 5-1.[1] The quantitative scores for the Challenges are relative scores that are valid in an ordinal sense within each R&T Area. They represent the results of linked, but separate, comparative analyses within each R&T Area and therefore should not be used to make absolute comparisons of the relative priority of various Challenges from different R&T Areas.

The QFD rankings in Table 5-1 should be taken as a guide rather than a prescription. Many of the R&T Challenges are considerably dissimilar in scope and content. In some cases, progress will require success in overcoming multiple linked Challenges. Other Challenges stand on their own. All of the R&T Challenges are considered worthy of NASA attention. In addition, many of the high-priority R&T Challenges have uses in fields other than civil aeronautics and are applicable to the missions of other federal agencies—DoD, DHS, and FAA, among others. Cooperative research between NASA and other agencies could therefore produce substantial national benefits.

The steering committee believes that the highest-priority R&T Challenges in each R&T Area should be included in the "foundation for the future" that forms the core of NASA s aeronautics program. The steering committee made no specific budgetary recommendations, in accordance with the statement of task for this study.

Success will require stable funding and consistent research priorities and planning, with the intent to pursue identified challenges for a decade or longer, as long as satisfactory progress continues. For NASA to exert strong leadership in key cutting-edge aeronautics R&T, it should focus on state-of-the-art research. Research plans should not be open-ended, however. An acceptable level of feasibility needs to be demonstrated (see suggested milestones in Appendixes A-E), and it is critical to have a process to stop or redirect efforts that fail to progress.

[1]The top 11 R&T Challenges are listed for Area A because the NASA priority scores for Challenges A10 and A11 are very close, and there is a large gap between the scores for Challenges A11 and A12.

Common Themes

In Chapter 4 the steering committee identified threads of commonality among the R&T Thrusts and the R&T Challenges from different R&T Areas. These threads have been captured as five Common Themes:

- Physics-based analysis tools
- Multidisciplinary design tools
- Advanced configurations
- Intelligent and adaptive systems
- Complex interactive systems

Each Theme encompasses enabling approaches that will contribute to multiple R&T Challenges.

Exploiting the synergies identified in each Common Theme would enable NASA s aeronautics program to make the most efficient use of available resources.

Key Barriers

The steering committee identified two key barriers in Chapter 4: certification and change management. If these barriers are not addressed, the Strategic Objectives will not be accomplished, even if individual R&T Challenges are successfully overcome.

As systems become more complex, methods to ensure that new technologies can be readily applied to FAA-certified systems become more difficult to validate. NASA

TABLE 5-1 Fifty-one Highest Priority Research and Technology Challenges for NASA Aeronautics, Prioritized by R&T Area

A Aerodynamics and Aeroacoustics	B Propulsion and Power	C Materials and Structures	D Dynamics, Navigation, and Control, and Avionics	E Intelligent and Autonomous Systems, Operations and Decision Making, Human Integrated Systems, Networking and Communications
A1 Integrated system performance through novel propulsion–airframe integration	B1a Quiet propulsion systems	C1 Integrated vehicle health management	D1 Advanced guidance systems	E1 Methodologies, tools, and simulation and modeling capabilities to design and evaluate complex interactive systems
A2 Aerodynamic performance improvement through transition, boundary layer, and separation control	B1b Ultraclean gas turbine combustors to reduce gaseous and particulate emissions in all flight segments	C2 Adaptive materials and morphing structures	D2 Distributed decision making, decision making under uncertainty, and flight path planning and prediction	E2 New concepts and methods of separating, spacing, and sequencing aircraft
A3 Novel aerodynamic configurations that enable high performance and/or flexible multi-mission aircraft	B3 Intelligent engines and mechanical power systems capable of self-diagnosis and reconfiguration between shop visits	C3 Multidisciplinary analysis, design, and optimization	D3 Aerodynamics and vehicle dynamics via closed-loop flow control	E3 Appropriate roles of humans and automated systems for separation assurance, including the feasibility and merits of highly automated separation assurance systems
A4a Aerodynamic designs and flow control schemes to reduce aircraft and rotor noise	B4 Improved propulsion system fuel economy	C4 Next-generation polymers and composites	D4 Intelligent and adaptive flight control techniques	E4 Affordable new sensors, system technologies, and procedures to improve the prediction and measurement of wake turbulence
A4b Accuracy of prediction of aerodynamic performance of complex 3-D configurations, including improved boundary layer transition and turbulence models and associated design tools	B5 Propulsion systems for short takeoff and vertical lift	C5 Noise prediction and suppression	D5 Fault-tolerant and integrated vehicle health management systems	E5 Interfaces that ensure effective information sharing and coordination among ground-based and airborne human and machine agents
A6 Aerodynamics robust to atmospheric disturbances and adverse weather conditions, including icing	B6a Variable-cycle engines to expand the operating envelope	C6a Innovative high-temperature metals and environmental coatings	D6 Improved onboard weather systems and tools	E6 Vulnerability analysis as an integral element in the architecture design and simulations of the air transportation system
A7a Aerodynamic configurations to leverage advantages of formation flying	B6b Integrated power and thermal management systems	C6b Innovative load suppression, and vibration and aeromechanical stability control	D7 Advanced communication, navigation, and surveillance technology	E7 Adaptive ATM techniques to minimize the impact of weather by taking better advantage of improved probabilistic forecasts
A7b Accuracy of wake vortex prediction, and vortex detection and mitigation techniques	B8 Propulsion systems for supersonic flight	C8 Structural innovations for high-speed rotorcraft	D8 Human–machine integration	E8a Transparent and collaborative decision support systems
A9 Aerodynamic performance for V/STOL and ESTOL, including adequate control power	B9 High-reliability, high-performance, and high-power-density aircraft electric power systems	C9 High-temperature ceramics and coatings	D9 Synthetic and enhanced vision systems	E8b Using operational and maintenance data to assess leading indicators of safety
A10 Techniques for reducing/mitigating sonic boom through novel aircraft shaping	B10 Combined-cycle hypersonic propulsion systems with mode transition	C10 Multifunctional materials	D10 Safe operation of unmanned air vehicles in the national airspace	E8c Interfaces and procedures that support human operators in effective task and attention management
A11 Robust and efficient multidisciplinary design tools				

should anticipate the need to certify new technology before its introduction, and it should conduct research on methods to improve the confidence in and the timeliness of certification. Methods might include new approaches (e.g., "design for certification"). If the civil aeronautics R&T program does not address this certification barrier, manufacturers and users will not be able to effectively exploit new technology in operations.

As discussed in Chapter 4, changing a complex interactive system such as the air transportation system is becoming more difficult due to the growing complexity of interactions between the various elements and the growing number of internal and external constraints. To effectively exploit the benefits of R&T to meet the Strategic Objectives, new tools and techniques are required to anticipate and introduce change. Without research to better define and develop change management tools and techniques, the inability to introduce change in a timely manner will serve as a barrier to exploiting the benefits offered by meeting the R&T Challenges.

OTHER FINDINGS OF IMPORTANCE

Allocation of Resources and Workforce Issues

NASA s aeronautics program is likely to operate in an environment of constrained resources for the foreseeable future. Nonetheless, the committee believes that NASA must meet its commitment to the nation as the leader of cutting-edge aeronautics research. This requires NASA to carry out, at a minimum, the following missions:

1. Perform cutting-edge, high-value aeronautics research in support of the nation s future industrial and government aeronautics needs.
2. Maintain in-house technical expertise to advise other parts of the U.S. government, including the FAA, the Environmental Protection Agency, and DoD, on relevant aeronautics issues.
3. Maintain state-of-the-art research, testing, computational, and analytical capabilities in support of the U.S. civil aviation community, including industry, academia, and the general public.
4. Facilitate the exchange of information on civil aeronautics R&T among academia, industry, U.S. government agencies, and the international regulatory community.
5. Provide aeronautics expertise and capabilities in support of NASA s space program.

For NASA to complete these missions in a constrained fiscal environment, the committee believes that NASA must consider the criteria listed below when considering whether to perform the work in-house by NASA engineers and technical specialists or externally by industry and/or universities:

- Specialized technical expertise of in-house and external organizations.
- Specialized facilities and capabilities, such as wind tunnels, simulators, laboratories, and analytical methods, that are available in-house and at external organizations.
- The requirement for NASA to have the expertise and experience necessary to be an informed buyer of aeronautics R&T.
- The requirement for NASA to provide independent technical advice to other federal agencies on aeronautics issues.

As of January 2006, NASA seemed intent on allocating 93 percent of NASA s aeronautics research funding for in-house use.[2] While the committee has no specific recommendation on the in-house/external split, it does not believe that such a split would serve the best interests of NASA or the nation. NASA R&T would likely suffer from the absence of relevant, specialized technical expertise, facilities, and capabilities (the first two criteria, above) without procuring expertise and capabilities from academia and, to a lesser degree, industry. Also, NASA would likely be limited in its ability to provide technology that supports the nation s future industrial aeronautics needs (Mission 1, above) without greater inclusion of industry. Furthermore, an insular approach to R&T would not leverage the creativity and multiplicative ideas that a more inclusive approach would likely produce. Technology transfer among government, universities, and industry would be more effective if all three groups have significant roles in NASA s research programs.

NASA researchers in some cases possess world-class technical expertise, and this expertise should be maintained. Furthermore, some level of technical expertise in a wide range of subjects is required for NASA to meet its obligations for conducting cutting-edge research, advising the government, and facilitating outside collaboration (Missions 1, 2, and 4, above). However, NASA should consider the capabilities of other research organizations before deciding whether to outsource R&T related to cutting-edge research, state-of-the-art capabilities, and the space program (Missions 1, 3, and 5, above).

A more balanced allocation of aeronautics R&T funding would allow NASA to form stronger partnerships with academia and industry. Stable funding of academic research grants, graduate student fellowships, student internships, and

[2]NASA s Aeronautics Research Mission Directorate has established four levels of research. NASA plans to allocate 7 percent of the total aeronautics budget to university and small company research at Level 1 (foundational research) (Wlezien, 2006b). Research at Level 2 (develop discipline-specific technologies and tools) and Level 3 (develop integrated, multidisciplinary methods and technologies) will be performed in-house by NASA. Research at Level 4 (develop integrated solutions for airspace and airport systems) will include collaboration with industry and partnerships with other agencies, but participating companies will be expected to pay their own way (NASA, 2006; Wlezien, 2006a).

cooperative NASA-university research centers would expand the intellectual pool contributing to NASA R&T, improve the skills of the nation s future aeronautics workforce, recruit new talent into the NASA workforce, and foster R&T projects that could not be done by NASA working alone. NASA should strive to foster close collaborative research with university partners, continuing a tradition of supporting basic research and new research directions in the academic environment.

Stronger partnerships with industry would help (1) identify technologically important problems, the answers to which can benefit the nation, (2) advance important precompetitive R&T that would not otherwise be done, (3) leverage industry research funded by other agencies or industry itself, (4) ensure that the results of NASA aeronautics research take into account relevant standards and practices, and (5) facilitate the transfer of research results to industry so that they find valuable, real-world applications. Ideally, programs that involve university, industry, and NASA researchers would lead to long-term benefits to NASA and the nation. A more inclusive approach to NASA s research would also increase the return on the government s investment in aeronautics R&T.

Taking Advantage of Advances in Cross-Cutting Technology Funded by Others

Most of the federal government s civil aeronautics research is done by NASA, but operational products are developed by manufacturers and operated by industry or the FAA. The FAA and industry also have the lead when it comes to certification issues. Within the federal government, no agency is responsible for all of the federal government s aeronautics research, nor is one agency focused exclusively on aeronautics research. This organizational structure mandates close cooperation and coordination between NASA s civil aeronautics R&T program and other federal agencies that support related research.

DoD conducts research on and development of many technologies important to national defense. At a fundamental technology level, much of the work sponsored by DoD is synergistic with NASA s civil aeronautics R&T, especially in transition modeling, reacting-flow physics, multiphase flows, novel aerodynamic configurations, morphing aerodynamic surfaces, adaptive cycle engines, high-speed and high-performance propulsion systems, integrated power systems, network-centric operations, control systems, UAVs, rotorcraft, impact dynamics, high-temperature and multifunctional materials and structures, low-cost materials and manufacturing, sensors, and multidisciplinary optimization.

Interactions with and coordination of research conducted by the FAA should be pursued in areas such as ATM and the measurement and modeling of aircraft wakes and weather phenomena. The large-scale weather models developed by the National Oceanic and Atmospheric Administration (NOAA) and the National Center for Atmospheric Research (NCAR) should be coordinated with the local terminal weather models important for prediction of wake vortex trajectories. Where synergistic research is being conducted, structured interactions and collaborations should be pursued.

Software-intensive systems are being developed in many industries. Applications relevant to civil aviation include highly autonomous systems, advanced decision aids, morphing aircraft, and advanced guidance systems. NASA should support these applications by collaborating with other organizations that are supporting research to write and qualify complex, safety-critical software in a more timely and cost-effective manner.

Significant opportunities also exist for NASA to collaborate with international research organizations, especially at the level of foundational physics. Structured processes should be developed to monitor international activities and plan appropriate collaborations.

With so many organizations involved in the development of new civil aeronautics technologies, advances often occur piecemeal, in areas of particular interest to individual stakeholders. Singularity of vision is needed to ensure that R&T programs develop all of the pieces necessary for game-changing advancements across the board. Within NASA, this is complicated by the fact that NASA s vision, resources, and energy must be shared between aeronautics and the much larger space exploration and space science programs—and the aeronautics program does not have a clear vision akin to the space program s vision of the human exploration of the Moon and Mars. Although organizational issues are beyond the purview of this study, the steering committee noted in the course of its deliberations that the factors cited above represent a potential barrier to the pursuit and implementation of aeronautics R&T. Because the issues transcend NASA, the steering committee observes that in the national interest, organizational options should be reviewed by a senior group commissioned by or within the federal government.

How Far Should NASA Advance Research?

NASA s congressionally mandated charter directs it to "preserve the role of the United States as a leader in aeronautical science and technology and the application thereof." To achieve this goal, NASA should embrace a comprehensive roadmap of foundational research that develops discipline-specific and multidisciplinary capabilities, including system-level design. The roadmap should include (1) progressive empirical validation up to and including a limited number of flight demonstration vehicles (X-planes), (2) technology readiness metrics, such as NASA s technology readiness levels (TRLs) (see Table 5-2), and (3) research partnerships with industry, academia, and other federal agencies. X-planes have played and will continue to play a crucial role

TABLE 5-2 NASA Technology Readiness Levels 1 to 9 for Aeronautics Research

Key Player	Stage of System Development	TRL	Description
Industry	System test and operations (TRL 8-9)	9	Actual system flight proven on operational flight
		8	Actual system completed and flight qualified through test and demonstration
	System/subsystem development (TRL 6-8)	7	System prototype demonstrated in flight environment
Government	Technology demonstration (TRL 5-6)	6	System/subsystem model or prototype demonstrated/validated in a relevant environment
		5	Component and/or breadboard verification in a relevant environment
	Technology development (TRL 3-5)	4	Component and/or breadboard test in a laboratory environment
	Research to prove feasibility (TRL 2-3)	3	Analytical and experimental critical function or characteristic proof of concept
		2	Technology concept and/or application formulated (candidate selected)
	Basic technology research (TRL 1-2)	1	Basic principles observed and reported

SOURCE: NASA, 2000.

in the advancement of aeronautical research by validating the practicality and robustness of specific technological advances. It is important to note that they are not limited to high TRL research. While an X-plane may represent a system prototype (TRL 7), it may also be used to observe basic phenomena, prove concepts, or validate a component or subsystem (TRL 1-6). TRLs provide a consistent and objective measure of technology maturation and progress. Research partnerships with external organizations provide an important mechanism to maintain the crucial links between NASA and the organizations that will use the results of NASA s aeronautics R&T. These partnerships also help to ensure that the research priorities of the aeronautics community as a whole remain relevant.

NASA is also charged with identifying, encouraging, and fostering cutting-edge R&T that will address important national goals but cannot be justified by individual companies in terms of return on investment. NASA should have clear criteria and metrics for entering, continuing to support, and leaving a research area (because of lack of progress or because goals have been achieved). Emerging areas are characterized by a multitude of ideas and approaches. Setting clear criteria for success and a timescale for evaluation allows research to focus on the most fruitful areas without prematurely abandoning an idea that still holds promise.

As noted in Table 5-2, NASA has historically supported research through TRL 6 and then transferred research results to industry, with the expectation that industry would continue development of new technologies through TRL 9. The steering committee, however, believes that different transfer points are often appropriate, because industry s interest in developing new technologies varies based on urgency and expected payoff. For urgent, high-payoff applications, for example, it may be sufficient for NASA to mature technologies to TRL 5.

When NASA is developing technologies for transfer to operational federal agencies such as the FAA, the committee believes that research results should normally be transferred to industry first, to ensure product support, enhancement, integration with other systems, and certification. For government agencies that include an R&D mission, agency-to-agency transfer is appropriate, and such transfers may occur at reasonably low TRLs (e.g., TRL 3).

Ground and Flight Test Capabilities

Since the creation of the small wind tunnel used by the Wright brothers to investigate aerodynamics for the first powered aircraft, advances in aeronautics have been closely tied to ground test facilities, such as simulators, wind tunnels, combined-environment load facilities, propulsion test cells, and acoustic facilities. These facilities allow repeatable and accurate assessment of physical processes and play a vital role in validating physical and computational models. To conduct the cutting-edge research outlined above, NASA must maintain world-class facilities and diagnostic capabilities. It should invest in research associated with improved facilities and diagnostics in coordination with DoD and industry. Furthermore, NASA should establish facility access and pricing policies that enable and encourage industry and academia to use NASA facilities. If costs are too high, they drive away potential customers, causing the price for remaining customers to spiral higher still. Eventually, underutilized tunnels are mothballed, and NASA loses testing capabilities and the expertise of workers who move on to other jobs or industries. NASA should seek a business model that will generate the optimal combination of income and utilization.

Flight test capabilities are required for research that cannot be adequately simulated in ground facilities. This research includes atmospheric propagation of noise and sonic booms, reacting-flow hypersonic phenomena, and large-scale propulsion–airframe integration.

While this study did not include a detailed assessment of facilities, some key facilities—and their deficiencies—are noted in Appendixes A-E. Facility concerns have been addressed in detail by studies devoted solely to this topic

(Anton et al., 2004; Kegelman, 2006; NRC, 1994, 2004). These reports have identified critical issues associated with the capabilities, funding, and use of national aeronautical test facilities, many of which have yet to be resolved.

RECOMMENDATIONS

The steering committee offers eight recommendations:

1. NASA should use the 51 Challenges listed in Table 5-1 as the foundation for the future of NASA s civil aeronautics research program during the next decade.
2. The U.S. government should place a high priority on establishing a *stable* aeronautics R&T plan, with the expectation that the plan will receive sustained funding for a decade or more, as necessary, for activities that are demonstrating satisfactory progress.
3. NASA should use five Common Themes to make the most efficient use of civil aeronautics R&T resources:[3]

- Physics-based analysis tools
- Multidisciplinary design tools
- Advanced configurations
- Intelligent and adaptive systems
- Complex interactive systems

4. NASA should support fundamental research to create the foundations for practical certification standards for new technologies.
5. The U.S. government should align organizational responsibilities as well as develop and implement techniques to improve change management for federal agencies and to assure a safe and cost-effective transition to the air transportation system of the future.
6. NASA should ensure that its civil aeronautics R&T plan features the substantive involvement of universities and industry, including a more balanced allocation of funding between in-house and external organizations than currently exists.
7. NASA should consult with non-NASA researchers to identify the most effective facilities and tools applicable to key aeronautics R&T projects and should facilitate collaborative research to ensure that each project has access to the most appropriate research capabilities, including test facilities; computational models and facilities; and intellectual capital, available from NASA, the Federal Aviation Administration, the Department of Defense, and other interested research organizations in government, industry, and academia.
8. The U.S. government should conduct a high-level review of organizational options for ensuring U.S. leadership in civil aeronautics.

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[3]The Common Themes are defined in Chapter 4.

Appendixes

A

R&T Challenges for Aerodynamics and Aeroacoustics

A total of 19 R&T Challenges were prioritized in the aerodynamics and aeroacoustics Area. Table A-1 shows the results. The R&T Challenges are listed in order of NASA priority. National priority scores are also shown.[1] This appendix contains a description of each R&T Challenge, including milestones and an item-by-item justification for each score that appears in Table A-1.[2]

A1 Integrated system performance through novel propulsion–airframe integration

Flow interactions in the region of the propulsion–airframe interface during takeoff, climb, and cruise pose a complex design problem. Design compromises have a significant effect on the aircraft efficiency and on radiated noise. Research into improved techniques for propulsion–airframe integration would improve aircraft flexibility and performance, especially as aircraft speeds increase. To meet this objective, both computational fluid dynamics (CFD) and experimental tests are indispensable. Improvements in the accuracy of predictions of three-dimensional (3-D) steady and unsteady interactions between external and internal aerodynamics and aeroacoustics are required to enable design of future aeronautical systems. These interactions include the effects of steady and dynamic distortion on engine operations and the effects of hot, reacting exhaust flows on vehicle aerodynamics. They are particularly important in the design of vertical and short takeoff and landing (V/STOL),[3] extremely short takeoff and landing (ESTOL), supersonic, and hypersonic airplanes. On V/STOL airplanes, exhaust jets are placed near the trailing edge of the wing where the aerodynamic stiffness of the high-speed flow increases wing lift by what is called the Jet Flap Effect (Spence, 1956). At supersonic speeds, adverse interactions between shock waves and boundary layers can increase drag and cause engine unstart. For many proposed hypersonic aircraft, the aircraft forebody is the inlet compression surface and the aircraft afterbody is the nozzle expansion surface, so that the airframe is part of the propulsion system. This is particularly the case with waveriders (Kuchemann, 1978). Propulsion–airframe integration has a significant impact on aircraft radiated noise. Improvements in test techniques and instrumentation are needed to characterize complex 3-D flow fields and acoustic radiation patterns. Key milestones include

- Validate the predictive capablity for 3-D mean and dynamic distortion at the propulsion–airframe interface.
- Validate the predictive capability of the impact of reacting exhaust flows on external aerodynamics.
- Validate the predictive capability of acoustic radiation patterns from integrated propulsion–airframe configurations.

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[1] The prioritization process is described in Chapter 2.

[2] The technical descriptions for the first 11 Challenges listed below contain slightly more detail than the technical descriptions for these Challenges as they appear in Chapter 3.

[3] VTOL airplanes can take off and land vertically. This includes tiltrotors, the AV-8 Harrier, and the JSF, for example. VTOL airplanes do not routinely take off or land vertically because of the range-payload penalty associated with the weight limitations of purely vertical operations. Rather, they use any available field length to develop some forward motion and wing lift during takeoff to increase the useful load (fuel plus payload). They tend to land vertically only at the end of the mission, when they are lighter, after burning fuel and/or dropping weapons.

STOL airplanes use high-lift systems to take off in less distance than conventional aircraft (typically a few thousand feet). Very few STOL aircraft can safely take off on runways shorter than 3,000 ft and none on runways less than 2,000 feet. (This class does not include ultralight aircraft, kit planes, etc. that can operate out of short fields due to their small size but do not have high-lift systems).

ESTOL airplanes would be able to safely take off on runways of 2,000 ft. They would have high-lift systems and thrust-to-weight ratios that are higher than conventional aircraft but not as high as VTOL aircraft. ESTOL aircraft have not yet been developed for commercial or military operations.

V/STOL refers to both VTOL and STOL airplanes that convert to fixed-wing flight after takeoff; it does not include helicopters.

TABLE A-1 Prioritization of R&T Challenges for Area A: Aerodynamics and Aeroacoustics

R&T Challenge		Strategic Objective: Capacity	Strategic Objective: Safety and Reliability	Strategic Objective: Efficiency and Performance	Strategic Objective: Energy and the Environment	Strategic Objective: Synergies with Security	Strategic Objective: Support to Space	National Priority	Why NASA?: Supporting Infrastructure	Why NASA?: Mission Alignment	Why NASA?: Lack of Alternative Sponsors	Why NASA?: Appropriate Level of Risk	Why NASA Composite Score	NASA Priority Score
	Weight	**5**		**3**		**1**			**$^1/_4$ each**					
A1	Integrated system performance through novel propulsion–airframe integration	9	3	9	9	9	9	**132**	3	9	3	9	**6.0**	**792**
A2	Aerodynamic performance improvement through transition, boundary layer, and separation control	9	3	9	9	3	3	**120**	3	9	3	9	**6.0**	**720**
A3	Novel aerodynamic configurations that enable high performance and/or flexible multimission aircraft	9	3	9	9	3	1	**118**	3	9	3	9	**6.0**	**708**
A4a	Aerodynamic designs and flow control schemes to reduce aircraft and rotor noise	9	1	3	9	3	1	**90**	3	9	3	9	**6.0**	**540**
A4b	Accuracy of prediction of aerodynamic performance of complex 3-D configurations, including improved boundary layer transition and turbulence models and associated design tools	3	3	9	3	3	3	**72**	9	9	3	9	**7.5**	**540**
A6	Aerodynamics robust to atmospheric disturbances and adverse weather conditions, including icing	9	9	3	1	9	1	**112**	3	9	3	3	**4.5**	**504**
A7a	Aerodynamic configurations to leverage advantages of formation flying	3	1	9	9	3	1	**78**	3	9	9	3	**6.0**	**468**
A7b	Accuracy of wake vortex prediction, and vortex detection and mitigation techniques	9	9	3	1	1	1	**104**	3	9	3	3	**4.5**	**468**
A9	Aerodynamic performance for V/STOL and ESTOL, including adequate control power	9	3	3	1	3	1	**76**	3	9	3	9	**6.0**	**456**
A10	Techniques for reducing/mitigating sonic boom through novel aircraft shaping	3	1	3	9	3	1	**60**	9	9	3	9	**7.5**	**450**
A11	Robust and efficient multidisciplinary design tools	3	3	9	9	3	3	**90**	3	9	3	3	**4.5**	**405**
A12	Accurate predictions of thermal balance and techniques for the reduction of heat transfer to hypersonic vehicles	1	1	3	1	9	9	**40**	9	9	3	9	**7.5**	**300**
A13	Low-speed takeoff and landing flight characteristics for access-to-space vehicles	1	3	1	1	3	9	**38**	3	9	9	9	**7.5**	**285**
A14	Efficient control authority of advanced configurations to permit robust operations at hypersonic speeds and for access-to-space vehicles	1	1	3	1	9	9	**40**	3	9	3	9	**6.0**	**240**
A15	Decelerator technology for planetary entry	1	1	1	1	3	9	**28**	3	9	9	9	**7.5**	**210**
A16	Low-Reynolds-number and unsteady aerodynamics for small UAVs	1	1	3	1	9	3	**34**	3	9	3	9	**6.0**	**204**
A17	Low-drag airship designs to enable long-duration stratospheric flight	1	3	1	3	9	1	**42**	3	3	3	9	**4.5**	**189**
A18	Prediction of communication capability through reentry trajectory and techniques to mitigate impact of communication blackouts	1	1	1	1	9	9	**34**	3	9	3	3	**4.5**	**153**
A19	Aircraft protective countermeasures based on a range of small deployed air vehicles	1	3	1	1	9	1	**36**	3	3	3	3	**3.0**	**108**

- Develop novel propulsion–airframe configurations for supersonic and hypersonic flight.

Relevance to Strategic Objectives

Capacity (9): Novel integration of the propulsion and airframe system will be required to meet the objectives of V/STOL and ESTOL airplanes and enable general operation on shorter runways, thereby enabling a significant increase in capacity.

Safety and Reliability (3): Development of techniques to monitor conditions and predict interactions between external and internal flows will allow automated responses to potentially dangerous flight conditions, which will enhance aircraft safety.

Efficiency and Performance (9): Improved integration of the propulsion system and airframe will facilitate development of aircraft with improved performance and efficiency.

Energy and Environment (9): Careful integration of engines with airframes offers the potential for significant noise reduction through selective shielding of the engine exhaust. In addition, lower overall aircraft drag will reduce fuel consumption and CO_2 emissions.

Synergies with National and Homeland Security (9): Predictive capabilities concerning engine–airframe integration will be applicable to all military aircraft.

Support to Space (9): Careful integration of the propulsion system with the airframe is required for air-breathing access-to-space vehicles.

Why NASA?

Supporting Infrastructure (3): NASA possesses both facilities and computational capabilities to investigate propulsion-airframe integration issues, but similar facilities and capabilities exist in DoD and, to a lesser extent, in industry.

Mission Alignment (9): Efforts aimed at development of an improved predictive capability that will lead to increased performance and efficiency of aircraft are very relevant to NASA s mission.

Lack of Alternative Sponsorship (3): Propulsion–airframe integration is being investigated by DoD and industry.

Appropriate Level of Risk (9): Improving the predictive capability of propulsion–airframe integration would likely enable a new class of highly integrated aircraft. The risk associated with the development of techniques to significantly improve performance, especially with respect to novel aircraft designs, is moderate.

A2 Aerodynamic performance improvement through transition, boundary layer, and separation control

Aircraft performance and efficiency strongly depend on the state of the boundary layer over different portions of the wing and fuselage. Viscous drag at subsonic, supersonic, or hypersonic speeds may be reduced by developing flow control techniques that actively detect and control the state of boundary layer flows with the goal of maintaining attached flow, controlling transition to turbulence, or reducing turbulent drag. For example, takeoff and landing distances strongly depend on the ability to maintain attached flow over the wing. On a typical commercial aircraft, approximately 25 percent of the drag is due to turbulent flow over the fuselage. If a drag reduction of just 1 percent were achieved in either of these areas, a large aircraft could reduce fuel consumption by up to 100,000 gallons per year while also reducing emissions.

Flow control has the potential for significant improvements in aircraft performance when coupled with revolutionary aircraft design configurations that are designed to optimally exploit the effects of flow control. New flow control techniques include steady and unsteady flow injection, vibrating elements such as piezoelectric and voice-coil actuators, and single-dielectric barrier discharge plasma actuators that are fully electric with no moving parts. All of these techniques have shown promise in laboratory experiments and some limited-scale flight tests. However, significant work is needed to refine these approaches and develop them further in order to transition them to full-scale designs.

Accurate models are needed for the actuator effects that can be incorporated into high-fidelity numerical flow simulations. The models would also be used to optimize the design of flow actuators to improve their flow authority and expand their usable flight regime. For flow control to achieve its full potential as an element in multidisciplinary design and optimization, the accuracy of numerical simulations and models needs to be validated, and they must be computationally efficient. Key milestones include

- Develop energy-efficient and flexible active flow control actuators.
- Develop improved models for the operation of flow actuators.
- Demonstrate techniques to incorporate these models into flow simulation schemes.
- Validate models and simulation schemes through comparison with experiments.

Relevance to Strategic Objectives

Capacity (9): Flow control has the potential to improve high-lift performance and therefore reduce takeoff and landing distances, which is a critical challenge for V/STOL and ESTOL airplanes and for accommodating larger conventional airplanes on existing runways. Flow control can also increase cruise efficiency, which reduces fuel usage even as capability increases.

Safety and Reliability (3): Some flow control concepts may improve safety and reliability by improving control of flow separation in unusual flight conditions. However, other concepts may introduce additional complexity that could have an adverse effect on reliability.

Efficiency and Performance (9): Flow control may greatly increase the efficient use of airport infrastructure through improved cruise efficiency. It also may be important for efficient supersonic flight.

Energy and Environment (9): Reduced cruise drag has a direct effect on fuel requirements and en route emissions. Reduced takeoff weight and improved low-speed performance reduces takeoff noise.

Synergies with National and Homeland Security (3): Flow control may improve the fuel efficiency of military aircraft and enhance the performance of aircraft with mission constraints related to separation control (e.g., short-field performance, aft loading ramps, and highly maneuverable aircraft). Transition control may be very important for military supersonic and hypersonic vehicles.

Support to Space (3): Transition management and separation control will impact air-breathing access-to-space vehicles and may be important to reentry heat transfer and to aerodynamics of vehicles in other planetary atmospheres.

Why NASA?

Supporting Infrastructure (3): NASA possesses relevant wind tunnels, infrastructure, and computational infrastructure. The tunnels permit high-Reynolds-number testing (e.g., the National Transonic Facility) and large-scale testing (e.g., National Full Scale Aerodynamics Complex operated by DoD at NASA Ames Research Center). NASA Dryden provides full flight testing capabilities. All of them are deemed critical to this Challenge. However, while NASA s infrastructure is very important, it is not unique in these areas.

Mission Alignment (9): This Challenge is broadly applicable to civil and military aeronautics.

Lack of Alternative Sponsorship (3): Because of the potentially high payoff, research relevant to this Challenge is conducted by many organizations outside NASA, including universities, industry, and DoD. Despite this, NASA could help coordinate these often disparate efforts and contribute directly to meeting this Challenge.

Appropriate Level of Risk (9): Despite the potential advantages of these technologies, they are not extensively used at present due mainly to a lack of understanding, tools, and validation—all areas to which NASA could contribute. This Challenge faces moderate risk.

A3 Novel aerodynamic configurations that enable high performance and/or flexible multimission aircraft

Most classes of aircraft configurations have remained constant for many years (e.g., the tube and wing of a subsonic transport, and the main rotor plus tail rotor of a helicopter). Novel aerodynamic configurations provide substantial opportunities to make long-term breakthroughs in aircraft capabilities. A number of innovative concepts have been proposed and pursued to differing levels. Examples include the blended wing body, canard rotor wing, oblique flying wing, and strut-braced wing. A sustained research program should be promoted to develop novel aircraft configurations, including further development of existing concepts where appropriate, with emphasis on achieving breakthroughs related to the high-priority Strategic Objectives. Specific examples of potential research include novel configurations with stepwise changes in performance, such as concepts with very high cruise efficiency to reduce fuel burn and emissions; STOL aircraft, V/STOL airplanes, and high-speed rotorcraft to achieve significant changes in capacity; and quiet supersonic aircraft to improve the efficiency of the air transportation system.

Other R&T Challenges would also contribute to enabling novel aerodynamic configurations. Advances in flight mechanics and propulsion–airframe integration (R&T Challenge A1) are required to make advanced concept airplanes viable and robust. Flow control (R&T Challenge A2) could significantly enhance the capability of novel configurations, since it could be assumed a priori in the design process rather than added as an improvement to an existing airplane. Research related to the Common Theme of physics-based analysis tools is needed to move beyond empirical design tools.[4] In addition, flight testing is a critical element of a successful research program in novel configurations. Key milestones include

- Develop a family of aircraft configurations with cruise efficiency twice as high as conventional aircraft.
- Demonstrate design approaches to develop novel configurations able to operate from small airfields.
- Validate the ability to predict the performance of novel airframe configurations using data from ground and flight tests.

Relevance to Strategic Objectives

Capacity (9): Novel configurations can enable stepwise changes in aircraft speed and payload, which are the primary independent variables of capacity. Additionally, V/STOL and ESTOL concepts can increase capacity because of their ability to use smaller airports.

Safety and Reliability (3): Advanced configurations can be designed to include safety and reliability requirements up front.

Efficiency and Performance (9): Existing aircraft configurations have been refined to the limits of today s technology. However, existing aircraft technologies can enable new

[4]"Physics-based" refers to the general use of scientific principles in the place of empirical data. It includes the use of principles from chemistry, biology, material science, etc.

classes of configurations that offer additional (and possibly significant) improvements.

Energy and Environment (9): Novel concepts offer significant potential for reducing fuel burn, noise, and emissions.

Synergies with National and Homeland Security (3): Some novel configurations may have military applications. For example, a multirole configuration has the potential to offer military and commercial capabilities from a common platform and a common crew.

Support to Space (1): This Challenge has no impact on this Objective.

Why NASA?

Supporting Infrastructure (3): NASA wind tunnels, simulators, and flight test facilities are important elements of the infrastructure required for the development of novel configurations, but industry and DoD also have relevant infrastructure.

Mission Alignment (9): Novel configurations offer significant potential for breakthroughs in aircraft performance. This Challenge is very relevant to NASA s mission.

Lack of Alternative Sponsorship (3): NASA has an important role to play in meeting this Challenge. However, some R&T will be pursued by industry. It is important that NASA pursue collaborative opportunities, where appropriate.

Appropriate Level of Risk (9): This Challenge faces high risk.

A4a Aerodynamic designs and flow control schemes to reduce aircraft and rotor noise

Reducing the aerodynamic noise from fixed- and rotary-wing aircraft at or near airports is a long-term issue that must be addressed to increase capacity at many airports. Design tools are needed at both the technology level and the aircraft system level, with particular attention to integrated solutions for aerodynamic and operational issues. This Challenge requires a balanced combination of physics modeling, tool development, and experiments.

For large fixed-wing transports, airframe noise on approach has become important, requiring efficient aerodynamic designs for flaps, ailerons, and landing gear that minimize noise radiation. Examples include smoothly varying section- and spanwise profiles to obtain high lift and low noise and high-drag/low-noise devices, which permit steep approaches, mitigating noise on the ground. Key research needs include a basic understanding of the fluid physics of cavity-like flows, unsteady flow–solid surface interactions, flow separation, development of physics-based source noise prediction methods, and development of improved computational aeroacoustic tools.

Many of today s airports now limit operations because of the noise emitted to the surrounding community. Future passenger growth at many airports will be limited if the noise levels emitted by the newer aircraft are not reduced further, thus adversely affecting capacity. Off-loading the main runway of regional jets by using ESTOL aircraft and rotorcraft, thus reducing congestion for larger passenger aircraft on the main runway, will dramatically increase capacity by allowing more takeoffs and landings at existing airports without increasing demand for runway usage (NRC, 2003; FAA, 2000). However, it will only be possible if these ESTOL aircraft and rotorcraft are quiet. To reduce takeoff and landing noise, such aircraft require the development of very high lift devices that are quiet and do not impose undue performance sacrifices Novel technologies are needed to decrease unsteady interactions between the propulsive lift devices and the lifting and control surfaces of the aircraft. These aircraft should also be designed to shield major sources of noise from the ground.

Minimizing impulsive noise generated by rotorcraft requires a better understanding of the aerodynamic state of the rotor, which is a strong function of the rotor blade structural properties. Both main and tail rotor noise are important, depending upon the configuration chosen. Methods of noise reduction include lowering the rotor rpm (which can degrade performance), reducing the major disturbances (shedding of tip vortices) to the following blades though rotor design and/or vortex-blade position control, integrating advanced control schemes for active rotorcraft noise reduction, and reducing the rotor response to vortex-induced disturbances. Also required are advances is the ability to predict rotor dynamic stall, to predict wake vortex dynamics, and to design rotor blades that minimize the time derivative of the blade s aerodynamic loading response to sharp-edged disturbances. Key milestones include

- Improve techniques for prediction and control of the aeroacoustics associated with high-lift devices, protuberances, and cavities for fixed-wing aircraft.
- Develop techniques for the prediction and design of quiet drag devices for fixed-wing aircraft.
- Improve understanding and modeling of unsteady fluid–structure interactions and resulting noise radiation for rotorcraft and fixed-wing aircraft.
- Demonstrate novel rotor system design tools that can be used to reduce rotor noise with minimum performance sacrifices for rotorcraft.

Relevance to Strategic Objectives

Capacity (9): Reducing aerodynamic noise of both fixed- and rotary-wing aircraft increases capacity by allowing more flights in and out of noise-impacted airports and by facilitating expansion of flight operations at satellite airports.

Safety and Reliability (1): This Challenge has little or no impact on this Objective.

Efficiency and Performance (3): Reducing noise can in some cases also improve aircraft performance. In a more general sense, reducing noise can improve the performance of the overall system by removing noise constraints that are currently impeding system efficiency.

Energy and Environment (9): Reducing noise reduces the environmental impact of aviation.

Synergies with National and Homeland Security (3): Noise reduction is important to make military aircraft more difficult to detect and to make operations near noise-sensitive areas more acceptable to the public.

Support to Space (1): This Challenge has no impact on this Objective.

Why NASA?

Supporting Infrastructure (3): Although NASA does not own all the nation s best aeroacoustic facilities, it does have access to a unique aeroacoustic facility for rotor noise testing: the 40 × 80 × 120-foot acoustically treated tunnel whose size allows far-field acoustic measurements of medium- and large-scale rotorcraft. However, this tunnel is now operated by the U.S. Air Force.

Mission Alignment (9): This Challenge is very relevant to NASA s mission.

Lack of Alternative Sponsorship (3): Industry, the FAA, and the DoD also carry out and sponsor work related to this Challenge.

Appropriate Level of Risk (9): This Challenge faces high risk because most of the easily attained techniques have already been incorporated into aircraft design.

A4b Accuracy of prediction of aerodynamic performance of complex 3-D configurations, including improved boundary layer transition and turbulence models and associated design tools

The aerospace industry lacks computational analysis and design tools that can rapidly and accurately predict complex flow behavior driven by boundary layer transition, flow separation, novel configurations, off-design operation, and multidisciplinary interactions. To meet this need, physics-based design tools must be developed and systematically validated in representative environments. Ideally, they should have the following attributes:

- Adaptive, intelligent, self-generating grids that are easily implemented using simple computer-aided design surface instructions, minimal boundary condition definition, and desktop operation.
- Seamless applicability over the continuum of fluid flows (speed regimes, phase, periodicity) and reference frames.
- Ability to accurately predict transitional and separated flows, validated through experimentation.
- Ability to fully describe the state of the fluid at any point in the solution domain, with useful information on the surfaces.
- Inverse design capability.

The benefit of technologies developed by this Challenge would be enhanced by the parallel development of multidisciplinary design tools to address complex nonlinear interactions and of methods to handle parameter uncertainties in a computationally efficient way (see Challenge A11). Key milestones include

- Develop improved techniques for the prediction of boundary layer transition on 3-D configurations and validate them against ground and flight test data.
- Demonstrate computationally efficient techniques to couple aerodynamic and structural analysis tools.
- Develop structured techniques for predicting performance in the presence of parameter uncertainties.

Relevance to Strategic Objectives

Capacity (3): Meeting this challenge will enable aircraft designs with breakthrough performance, yielding higher capacity.

Safety and Reliability (3): A better understanding of these phenomena will help to identify and mitigate unexpected transitional and separated flows, leading to increased safety.

Efficiency and Performance (9): Improved analysis tools will enable designs with higher efficiency that go beyond current performance limitations caused by nonoptimized and compromised designs.

Energy and Environment (3): The analysis tools will enable designs with higher aerodynamic efficiency and hence reduced fuel burn.

Synergy with National and Homeland Defense (3): Improvements in aerodynamic prediction capabilities are expected to improve DoD aircraft development.

Support to Space (3): Boundary layer transitional behavior through multiple speed regimes remains one of the large uncertainties for air-breathing access-to-space vehicles. Improvements in predictive capabilities are likely to improve the potential performance of these vehicles by reducing design margins.

Why NASA?

Supporting Infrastructure (9): NASA possesses some of the most advanced computational fluids modeling and empirical validation tools in the world, across multiple speed regimes and environments.

Mission Alignment (9): NASA s historical CFD code development provides a foundation for much of industry s design codes today; this Challenge is very relevant to NASA s mission.

Lack of Alternative Sponsorship (3): Industry and DoD have a broad interest in this Challenge.

Appropriate Level of Risk (9): Transitional and separated flows remains a largely unsolved frontier in aeronautics. This Challenge faces significant risk.

A6 Aerodynamics robust to atmospheric disturbances and adverse weather conditions, including icing

Adverse weather conditions, including storms and icing conditions, significantly reduce the capacity and reliability of the air transportation system. Adverse weather also degrades system safety. This issue is of importance to both civil and military aviation. Research is needed to improve the ability to predict and monitor environmental conditions and develop aerodynamic designs and techniques that are robust to adverse conditions.

At present, wind-shear warning systems are built into commercial aircraft, icing hazards are handled by regulatory constraints on flight operations, and prediction techniques are largely empirical. Low-cost techniques to measure environmental conditions ahead of an aircraft should be developed. Examples of promising techniques include microwave, lidar, and laser-acoustic measurement techniques. Efforts to miniaturize and reduce the cost of the measurement equipment should be supported. Techniques to predict and mitigate the impact of adverse environmental conditions on the aircraft operation should be improved. Required improvements include the development of models to predict the impact of multiphase, nonequilibrium situations encountered under icing conditions; validation of icing prediction capabilities to enable a reduction in the high cost of aircraft and helicopter icing certification; and models for the complex-flow, time-dependent, 3-D interactions encountered during wind shear or ambient turbulence on the aircraft flowfield. Key milestones include

- Develop and validate 3-D icing prediction tools.
- Demonstrate systems with improved spatial and temporal measurements of upstream environmental conditions.
- Develop high-bandwidth techniques to respond to and mitigate the impact of upstream environmental conditions.

Relevance to Strategic Objectives

Capacity (9): Improving operations in adverse weather conditions will increase capacity by allowing more on-time flights and fewer diversions to other airports.

Safety and Reliability (9): Identifying and mitigating adverse environmental conditions will reduce accident rates and increase the reliability of the air transportation system.

Efficiency and Performance (3): Through mitigating the adverse impacts of weather, air transportation resources can be optimally used with fewer operational constraints.

Energy and Environment (1): This Challenge has no impact on this Objective.

Synergies with National and Homeland Defense (9): DoD and DHS operations will be enhanced if adverse weather conditions become less of a constraint. In particular, DoD capabilities are substantially enhanced if U.S. military forces can operate effectively in weather conditions that degrade the effectiveness of enemy forces, and if enemy forces cannot use adverse weather as cover.

Support to Space (1): Most space operations have the luxury of waiting for favorable environmental conditions. This Challenge has little impact on this Objective.

Why NASA?

Supporting Infrastructure (3): NASA possesses icing wind tunnels and research aircraft that complement infrastructure in academia and industry.

Mission Alignment (9): This Challenge is very relevant to NASA s mission.

Lack of Alternative Sponsorship (3): Both the FAA and industry conduct work related to this Challenge.

Appropriate Level of Risk (3): Advances related to this Challenge can reasonably be expected within the next decade.

A7a Aerodynamic configurations to leverage advantages of formation flying

Formation flight is currently used by military airplanes for a variety of operational reasons, although rarely for drag reduction. Recent breakthroughs in accurate navigation and control make possible extended precision formation flight in cruise and permit exploiting favorable interference to reduce vortex drag. Although this phenomenon is well known, the magnitude of the potential savings is not widely appreciated. Three airplanes flying in formation and designed to best exploit these effects could reduce vortex drag by more than 50 percent in cruise, a greater reduction than that obtainable by extensive laminar flow control on the wing. This would mean roughly a 20 percent reduction in total drag under identical operating condition. However, with less induced drag, the optimum altitude increases, reducing viscous drag as well. The net result is almost a 30 percent reduction in total drag. Unlike the tight formations required for military applications, drag savings are possible even with longitudinal separations of several miles (Spalart, 1998), reducing safety concerns associated with formation flight. Initial NASA work on autonomous formation flight has identified some of the technology requirements for achieving these savings, but considerable research remains in both control methodology and aerodynamic design to take most advantage of the concept. Applications to cargo airplanes, rotorcraft, and even supersonic flight are possible but have not been studied extensively. Aerodynamic challenges include vortex location prediction, sensing and control, and wing design for efficient high-lift cruise. Key milestones include

- Develop improved methods to accurately predict wake vortex evolution.
- Demonstrate design tools for evaluation and optimization of multiple interacting airplanes.
- Validate models and tools for formation flying using ground and flight experiments to evaluate real atmospheric effects.

Relevance to Strategic Objectives

Capacity (3): Formation flying may have some effect on capacity through reduced takeoff weight, which will lead to reduced spacing requirements and fewer noise-related restrictions. Formation flying will also increase en route density, leading to increased capacity.

Safety and Reliability (1): Formation flying introduces additional safety concerns, some of which are ameliorated with large longitudinal spacing.

Efficiency and Performance (9): Reduced fuel consumption and the potential for more efficient cargo delivery systems will improve efficiency and performance.

Energy and Environment (9): Reduced cruise drag has a direct effect on fuel requirements and en route emissions. Reduced takeoff weight and improved low-speed performance reduces takeoff noise.

Synergies with National and Homeland Security (3): Formation flying may improve military airplane fuel efficiency in long-duration operations.

Support to Space (1): This Challenge has no impact on this Objective.

Why NASA?

Supporting Infrastructure (3): NASA has flight-testing and computational infrastructure important to this Challenge. Recent experience with formation flight testing is a key point.

Mission Alignment (9): This research is broadly applicable to civil and military aeronautics.

Lack of Alternative Sponsorship (9): Despite some interest from DoD, this R&T Challenge is sufficiently unconventional, new, and uncertain that sponsorship from other sources is unlikely.

Appropriate Level of Risk (3): There is a very high risk that it will not be possible to implement the technology in a practical way for civil aeronautics.

A7b Accuracy of wake vortex prediction, and vortex detection and mitigation techniques

Wingtip vortices produced by airplanes present a danger to following aircraft, so airplane designs and techniques that mitigate the strength of these vortices, techniques to locate and determine their strength, and techniques to predict their propagation and decay are important factors in minimizing aircraft separation and enhancing safety.[5] (Since aircraft lift is intimately tied to the production of circulation, these vortices cannot be completely eliminated.) Currently, aircraft separation standards are set by conservative estimates of the wake vortex trajectory (generally a sinking trajectory, but also affected by local weather conditions) and decay rate. Techniques to measure the characteristics of upstream wake vortices include lidar and laser-acoustic techniques, but these technologies are currently expensive (limiting their use to larger aircraft) and are less reliable than desired. Research into techniques to predict the formation, trajectory, and decay of vortices needs to be performed. Key milestones include

- Develop numerical techniques to predict accurately wingtip vortex trajectory, strength, and dissipation.
- Validate numerical methods with experiments and flight testing.
- Integrate local weather prediction techniques into larger-scale weather models.
- Demonstrate low-cost techniques for locating and measuring the strength of wake vortices for ground-based and aircraft-based applications.
- Investigate aircraft designs that mitigate the strength of wake vortices.

Relevance to Strategic Objectives

Capacity (9): Accurate prediction and measurement of wake vortex strength and trajectory can reduce airplane spacing requirements, increasing capacity.

Safety and Reliability (9): An improved understanding of wake vortex dynamics will improve safety of following aircraft. Techniques aimed at minimizing the strength or increasing the dissipation rate will present weaker vortices to following aircraft.

Efficiency and Performance (3): Technologies aimed at reducing aircraft spacing will improve the efficiency and performance of the air transportation system.

Energy and Environment (1): This Challenge has no impact on this Objective.

Synergy with National and Homeland Defense (1): This Challenge has minimal impact on this Objective.

Support to Space (1): This Challenge has no impact on this Objective.

Why NASA?

Supporting Infrastructure (3): NASA and the aircraft industry have conducted research into wake physics modeling

[5]The scope of this Challenge does not include and would not directly apply to helicopter blade wakes.

and measurement; both have important infrastructure to bring to this area.

Mission Alignment (9): This Challenge is very relevant to NASA s mission.

Lack of Alternative Sponsorship (3): Relevant research conducted by NASA is synergistic and closely aligned with similar work of the FAA.

Appropriate Level of Risk (3): Good progress can be expected in this area within the next decade.

A9 Aerodynamic performance for V/STOL and ESTOL, including adequate control power

Since 2001, the U.S. aviation industry has undergone a profound change. On many routes, regional jets have replaced propeller-driven aircraft, which used different runways and flew at lower altitudes than the large commercial transports. Regional jets are using the same runways and airways as the large transports. This increases congestion and delays at major airports, which degrades the performance of the entire air transportation system.

Powered lift (V/STOL and ESTOL) airplanes and rotorcraft may provide solutions to this problem. V/STOL jets with highly swept wings can operate from the short runways previously used by straight-wing propeller-driven transports. These aircraft, together with rotorcraft, may also be able to operate from taxiways and other paved areas at major airports or smaller regional airports. Any of these applications would relieve congestion on the main runways at major airports. In responding to natural disasters and carrying out military operations, low-cost VTOL tactical transports would be able to operate from short, austere landing fields near the focus of attention (e.g., the location of injured civilians or troops, battle areas, and landslides).

These aircraft will require advances in aerodynamics; propulsion; acoustics; stability and control; structures and materials; and guidance, navigation, and communications. Specific aerodynamic issues that require attention include development of a low-drag, high-lift system, simple boundary layer control systems to prevent wing leading-edge separation, systems to provide pitch trim and control power at low speeds, a reversing deflecting exhaust nozzle, and wing design and fuselage shaping to reduce cruise drag in the transonic regime.

An important task for research related to rotorcraft and fixed-wing VTOL aircraft is improving hovering and cruise efficiency. Reductions in downward forces in near-hovering flight dramatically improve the payload capability of tilt-rotor and powered-lift aircraft. Active control of large separation regions on these aircraft through blowing, zero-mass effectors and integrated mechanical devices are promising methods of reducing download. Active twist control of the rotor also allows the rotorcraft to be designed to better match the hover and cruise design conditions, thereby improving efficiency. Active control of separation regions and smart design guided by high-fidelity codes will decrease cruise drag and greatly improve the performance of V/STOL airplanes and rotorcraft. Validated codes require interdisciplinary research efforts as well as efforts to improve separation prediction and control. Key milestones include

- Develop low-drag, high-lift systems.
- Demonstrate systems to provide pitch trim and control power at low speeds.
- Develop new techniques for active twist control of rotors.
- Demonstrate low-cost, simple flow control techniques for prevention of leading-edge separation from V/STOL wings.
- Improve wing design and fuselage shaping to reduce transonic cruise drag.

Relevance to Strategic Objectives

Capacity (9): This Challenge could greatly increase capacity by shifting regional jets from the major runways to smaller runways and/or taxiways and by enabling the use of smaller regional airports.

Safety and Reliability (3): Developing adequate control power at high lift, low speed would increase safety.

Efficiency and Performance (3): Novel methods of improving the performance of V/STOL airplanes (e.g., download reduction and avoiding flow separation regions in cruise) and rotorcraft can improve their efficiency.

Energy and Environment (1): This Challenge has no impact on this Objective.

Synergies with National and Homeland Security (3): Mobility, especially over unprepared or short fields, is very important for quick-response situations. V/STOL and ESTOL airplanes would enhance these capabilities.

Support to Space (1): This Challenge has no impact on this Objective.

Why NASA?

Supporting Infrastructure (3): Large-scale testing is critical to this Challenge. The best large-scale ground testing facility is the 40 × 80 × 120 ft tunnel at NASA Ames. NASA has access to this facility, although it is now operated by the U.S. Air Force. NASA also has smaller scale facilities that can support this Challenge.

Mission Alignment (9): This Challenge capitalizes on NASA in-house expertise in powered lift and rotorcraft development and is very relevant to NASA s mission.

Lack of Alternative Sponsorship (3): Industry and DoD also carry out and sponsor work related to this Challenge.

Appropriate Level of Risk (9): This Challenge faces high risk.

A10 Techniques for reducing/mitigating sonic boom through novel aircraft shaping

Safe, efficient, cost-effective, environmentally acceptable supersonic flight over land remains elusive nearly 60 years after airplanes broke the sound barrier. The principal remaining problems are sonic boom mitigation, public acceptance, and sustained supersonic flight performance. Today, federal regulations prohibit civil supersonic flight over land. If this regulatory barrier can be overcome, it will probably stimulate investment that would overcome the other barriers and help usher in a new era of time-critical air travel. Building on the recent in-flight validation of NASA s shaped sonic boom persistence theory, a robust and comprehensive plan of research for technology maturation and tool development should be pursued to determine if practical supersonic airplanes can be developed whose sonic boom is acceptable to the public (Pawlowski et al., 2005). Such a plan should comprise the determination of what level of sonic boom is acceptable to the public; community exposure testing; aircraft shaping techniques that result in low-amplitude, acceptable acoustic signature with minimal performance impact; critical propulsion–airframe integration technologies commensurate with low-boom design; aircraft and acoustic scaling methodologies; sensitivities to off-design conditions under a variety of atmospheric conditions; rapid and inverse computational design tools that address multiple design constraints; systematic validation through ground and flight test; and metrics to assess progress and guide continuation according to the plan. This Challenge is closely tied to Challenge B8. Key milestones include

- Develop guidelines for allowable exposure of the public to sonic booms.
- Develop accurate techniques for the prediction of sonic boom propagation through the atmosphere under realistic environmental conditions.
- Demonstrate novel aircraft shapes that minimize sonic boom levels.

Relevance to Strategic Objectives

Capacity (3): Enabling supersonic flight over land will increase capacity by moving airplanes through the system more rapidly, although, at least initially, such a capability will affect only a small segment of the population.

Safety and Reliability (1): This Challenge has no impact on this Objective.

Efficiency and Performance (3): Success in this Challenge will usher in a new era of time-critical travel.

Energy and Environment (9): This Challenge will profoundly reduce the noise produced by supersonic airplanes.

Synergy with National and Homeland Defense (3): This Challenge will enable quiet supersonic airplanes, which will also benefit military missions.

Support to Space (1): This Challenge has no impact on this Objective.

Why NASA?

Supporting Infrastructure (9): NASA possesses unique empirical facilities, including a supersonic flight test corridor, and extensive code, test, and measurement resources, reflecting NASA s large historical investment in supersonic airplane programs such as the High Speed Research Program.

Mission Alignment (9): This Challenge is very relevant to NASA s mission.

Lack of Alternative Sponsorship (3): Broad interest has been shown by industry.

Appropriate Level of Risk (9): Achievability of efficient, cost-effective, environmentally acceptable supersonic cruise airplanes remains highly uncertain, and the risk associated with research aimed at sonic boom reduction is high.

A11 Robust and efficient multidisciplinary design tools

Multidisciplinary design tools are pervasive in aeronautics. A multidisciplinary, integrated system-level design approach to assessing potential costs, benefits, and risks would help advance aerodynamic technologies, shorten the design cycle time for conventional aircraft, and develop novel aircraft configurations. Tools that couple a small number of disciplines have reached a level of maturity and fidelity that should be exploited by design tools. For example, aeroelastic design tools are now within reach that couple CFD and finite-element analyses for full aircraft configurations. More recently, multidisciplinary design tools have begun to incorporate a broader range of disciplines, and techniques such as multidisciplinary design optimization (MDO) have been used to a limited extent in aircraft conceptual design.

One of the major limitations of past efforts to create MDO tools has been a low level of fidelity, driven by a lack of physics-based models that are sufficiently efficient for use at the system design level. In addition, MDO tools have often been developed and applied for very specific applications and flight conditions, so they lack flexibility. Key challenges associated with next-generation multidisciplinary design tools include tool fidelity, computational efficiency, and the ability to handle parameter uncertainties. The practical resolution of these challenges will require fundamental research efforts in physics-based models for use in design tools (see R&T Challenge A4b), new design methodologies that can seamlessly manage models of multiple fidelities for the various components of the system, methods to increase the computational efficiency of tools, methods to handle complex interactions with high accuracy, and automated techniques for handling and propagating parameter uncertainties throughout the design. Key milestones include

- Develop and validate physics-based models to predict performance for novel aircraft configurations.
- Assess a family of aircraft configurations with major improvement in cruise efficiency, including a quantitative description of the benefits and risks.
- Assess novel concepts for flexible multimission aircraft, including a description of potential benefits in performance and cost.
- Conceive design approaches to develop novel V/STOL and ESTOL configurations.
- Validate design codes to predict the performance of novel airframe configurations by comparing code predictions with ground and flight tests.

Relevance to Strategic Objectives

Capacity (3): The development of improved predictive capabilities and multidisciplinary tools will lead to flexible aircraft capable of increasing capacity.

Safety and Reliability (3): A capability for design under uncertainty will help improve safety and reliability.

Efficiency and Performance (9): Multidisciplinary design tools are a key enabling technology for achieving revolutionary aircraft designs with improved performance.

Energy and Environment (9): The novel designs that could be achieved with these tools could have a significant impact on energy and environmental issues.

Synergies with National and Homeland Defense (3): Multidisciplinary design tools are applicable to military aircraft.

Support to Space (3): Multidisciplinary design tools could also be used to improve space vehicle design.

Why NASA?

Supporting Infrastructure (3): NASA has a strong track record of R&T in system design tools and multidisciplinary design optimization. NASA has relevant computational infrastructure, although it is not unique.

Mission Alignment (9): This Challenge is very relevant to NASA s mission.

Lack of Alternative Sponsorship (3): Both industry and other government agencies are pursuing work in this Challenge, although NASA has a unique opportunity to provide a bridge between academic research and industrial needs.

Appropriate Level of Risk (3): This Challenge faces low risk.

A12 Accurate predictions of thermal balance and techniques for the reduction of heat transfer to hypersonic vehicles

Air-breathing access-to-space and reentry vehicles must operate in a stressing aerothermodynamic environment that requires high-performance, robust thermal protection systems (TPSs). The cost and feasibility of air-breathing launch vehicles are extremely sensitive to mass. Therefore, more accurate techniques are needed to (1) predict aerothermal loads (and thus decrease the design margins associated with the TPS) and (2) minimize both local and integrated heat transfer to the vehicle, which can significantly increase system performance. Specific needs include improved predictions of how the following factors affect heat transfer in the hypersonic environment: ablation, boundary layer transition, highly cooled walls (which affects boundary layer turbulence), wall chemistry (including catalytic effects), and radiating shock layers.

Relevant techniques include novel aerodynamic shaping, active flow control, transpiration cooling, and emissivity control. Research is also required to determine the utility of plasma aerodynamic and magnetohydrodynamic flow manipulation for heat transfer reduction. Key milestones include

- Improve models for predicting the effects of ablation on heat transfer.
- Develop a high-fidelity model for radiating shock layers.
- Develop turbulence models validated against experimental data for highly cooled walls.

Relevance to Strategic Objectives

Capacity (1): This Challenge has little impact on this Objective.

Safety and Reliability (1): This Challenge has little impact on this Objective.

Efficiency and Performance (3): Development of accurate heat transfer prediction techniques and mitigation of local high-heat-transfer regions will improve the performance of supersonic and hypersonic vehicles.

Energy and Environment (1): This Challenge is principally aimed at hypersonic vehicle applications, so this Challenge has no impact on this Objective.

Synergies with National and Homeland Defense (9): Development of robust supersonic and hypersonic systems can help address DoD missions in areas such as missile defense, time-critical strike, prompt global strike, and access to space.

Support to Space (9): Heat transfer is an important issue associated with air-breathing access-to-space and reentry systems.

Why NASA?

Supporting Infrastructure (9): NASA possesses unique capabilities related to hypersonic aerothermodynamics, including NASA Langley s Mach 10 aerothermodynamic wind tunnel and 8-ft high-temperature tunnel.

Mission Alignment (9): Hypersonic aerothermodynamics is a fundamental enabling R&T Challenge that is very relevant to NASA s mission.

Lack of Alternative Sponsorship (3): Both NASA and DoD conduct research to improve techniques to predict and mitigate the adverse impacts of heat transfer.

Appropriate Level of Risk (9): This Challenge faces moderate risk.

A13 Low-speed takeoff and landing flight characteristics for access-to-space vehicles

Air-breathing access-to-space vehicles capable of horizontal takeoff and landing hold significant promise in providing low-cost access to space. Mission and operational flexibility is greatly enhanced by the ability to operate from sites similar to those utilized for conventional aircraft. However, factors such as high wing sweep, sharp leading edges, and use of a propulsion system designed for hypersonic flight significantly increase runway length and require greatly modified flight corridors relative to conventional aircraft.

Research in this area should include, but not be limited to, development and evaluation of high-lift systems, active and passive flow control, consideration of two-stage-to-orbit configurations, optimum fuselage and wing shaping, morphing structures, and configurations with enhanced propulsion–airframe integration for improved low-speed flight characteristics. Strategies to improve takeoff and landing performance without significantly impacting payload capacity, range, fuel, and structural weight and cost are vital because the overall efficiency and cost of space launch vehicles is very sensitive to weight. More accurate tools are needed to predict the effects of flow control, vehicle shaping, and propulsion–airframe integration techniques on boundary layer behavior and flow separation. In addition, integrated system analysis tools must be developed and validated to predict how modifications to improve takeoff and landing performance will affect vehicle performance throughout the flight profile. The aerodynamic tools and novel strategies for improving low-speed performance must be validated by relevant ground and flight tests. Key milestones include

- Validate predictive capability for integrated vehicle aerodynamics in the presence of the runway.
- Develop strategies to maintain efficient low-speed aerodynamic performance for hypersonic vehicle designs.

Relevance to Strategic Objectives

Capacity (1): This Challenge will have no impact on this Objective in the time frame considered.

Safety and Reliability (3): Some of the flow control and separation mitigation techniques that address this Challenge may be applicable to subsonic commercial aircraft low-altitude flight and provide improvement in safety and reliability during the takeoff and landing phases of flight.

Efficiency and Performance (1): This Challenge has little to no impact on this Objective.

Energy and Environment (1): This Challenge has little to no impact on this Objective.

Synergies with National and Homeland Security (3): Some of the flow control and separation mitigation techniques that address this Challenge may be applicable to current and future high-speed military aircraft.

Support to Space (9): This Challenge could significantly improve the operational flexibility of access-to-space missions.

Why NASA?

Supporting Infrastructure (3): NASA possesses wind tunnels that are well suited for this Challenge. NASA expertise and computational facilities are appropriate but not unique.

Mission Alignment (9): This Challenge is very relevant to NASA s space exploration mission.

Lack of Alternative Sponsorship (9): Horizontal takeoff and landing vehicles will not be developed without federal investment, and the fundamental physics studies on boundary layers and separation are appropriate long-term research efforts for NASA. No significant, sustained work is done in this area by other government entities or industry.

Appropriate Level of Risk (9): This Challenge faces high risk.

A14 Efficient control authority of advanced configurations to permit robust operations at hypersonic speeds and for access-to-space vehicles

Hypersonic vehicles have the potential to provide affordable access to space, safe and predictable entry from space, flight in other planetary atmospheres, prompt global reach, and missile defense. Aerodynamic configurations optimized for hypersonic cruise or acceleration present significant design challenges. They can prove inefficient at off-design conditions, their performance is affected by interactions with the aerodynamic flow through the engine flow path, and they frequently require control at high altitudes.

Control of vehicles operating in this regime will require a better physics-based understanding of the flow field characteristics. The characterization and prediction of the effect of boundary layer transition on aerodynamic configurations remains a significant challenge. More accurate knowledge of the state of the boundary layer, transition location, areas of separation, and certain viscous interactions, including shock-wave–boundary-layer interaction, will facilitate development of configurations with adequate control authority. The implementation of flow control concepts through the use of novel actuation (e.g., plasma/magnetohydrodynamic concepts) may prove useful. In addition, characterizing the salient physics of improved measurement techniques and the use of high-quality test data to validate computational techniques will be required to adequately design and develop configurations with control authority at hypersonic speeds. Key milestones include

- Develop techniques to accurately predict flow control authority in shock-dominated flows and in transitional flows.
- Demonstrate novel flow control techniques applicable to hypersonic vehicles.
- Develop novel ground and flight test instrumentation techniques for validation of analytical and computational models.

Relevance to Strategic Objectives

Capacity (1): This Challenge has no impact on this Objective.

Safety and Reliability (1): This Challenge has no impact on this Objective.

Efficiency and Performance (3): Research in this Challenge will extend the understanding of complex fluid physics, which will increase understanding at lower speeds as well.

Energy and Environment (1): This Challenge has no impact on this Objective.

Synergies with National and Homeland Security (9): Most high-speed applications will benefit from the improved control authority techniques investigated by this Challenge.

Support to Space (9): This Challenge provides a significant contribution to space exploration and access-to-space missions.

Why NASA?

Supporting Infrastructure (3): NASA possesses some relevant capabilities in the areas of hypersonic aerodynamics, but several important assets exist at DoD as well.

Mission Alignment (9): Hypersonic aerodynamics is a fundamental enabling technology that is very relevant to NASA s mission.

Lack of Alternative Sponsorship (3): Both NASA and DoD conduct research associated with improvements in stability and control of hypersonic vehicles to better understand and control vehicle flight dynamics.

Appropriate Level of Risk (9): This Challenge faces high risk.

A15 Decelerator technology for planetary entry

Effective and reliable decelerator technologies for Earth reentry and planetary entry are needed to support NASA s space exploration mission. Such technologies must yield acceptable deceleration loads (which are most stringent for crewed vehicles). In addition, some missions require the generation of lift for improved cross-range and control of the entry trajectory. The key task for this Challenge is to provide the required aerodynamic loads in a robust and reliable system while yielding efficient, low-mass thermal protection.

Relevant research includes characterization of planetary atmospheric conditions and chemistry; development and evaluation of optimum vehicle shapes and novel configurations; use of parachutes, parafoils, ballutes; active and passive flow control; and accurate prediction of aerodynamic and thermal loads and trajectories during aerocapture and aero-assisted orbital transfer operations. Improved accuracy is needed in tools designed to predict thermal loads in the planetary atmosphere under consideration and to predict unsteady aeroelastic effects on structures that are highly flexible or whose shape may vary (e.g., due to ablation). In addition, integrated system analysis tools are also needed. Validation of the aerodynamic tools and novel strategies for improving performance and reliability of decelerator technologies requires ground and flight testing. Key milestones include

- Conceive novel approaches for deceleration in planetary atmospheres.
- Improve the computational efficiency of time-dependent aerothermal prediction tools.
- Develop integrated system analysis tools for planetary entry system design.

Relevance to Strategic Objectives

Capacity (1): This Challenge has no impact on this Objective.

Safety and Reliability (1): This Challenge has no impact on this Objective.

Efficiency and Performance (1): This Challenge has no impact on this Objective.

Energy and Environment (1): This Challenge has no impact on this Objective.

Synergies with National and Homeland Security (3): Ballistic and hypersonic cruise missiles will derive some benefit from the thermal protection elements of this Challenge.

Support to Space (9): This Challenge significantly contributes to space exploration and access-to-space missions.

Why NASA?

Supporting Infrastructure (3): NASA possesses relevant and unique high-enthalpy tunnels and reacting flow expertise. Other tunnels, materials testing, and computational facilities needed for this topic also exist elsewhere (e.g., the DoD facilities at the Arnold Engineering and Development Center and the Calspan–University of Buffalo Research Center).

Mission Alignment (9): The Challenge is very relevant to NASA s space exploration mission.

Lack of Alternative Sponsorship (9): Only NASA has the mission of space exploration, so no work is done in this Challenge by other government entities or by industry without NASA s involvement.

Appropriate Level of Risk (9): The fundamental physics studies on heat transfer and prediction require substantial long-term research. NASA, however, has unique thermal protection and planetary operations experience. This Challenge faces moderate risk.

A16 Low-Reynolds-number and unsteady aerodynamics for small UAVs

This Challenge deals with the special aerodynamic issues associated with small UAVs (wing spans on the order of 6 inches) that are capable of high maneuverability and flight in confined spaces. These vehicles are of interest to DoD and DHS for missions that involve autonomous reconnaissance in urban areas, including inside buildings. The vehicles are also relevant to flight in the martian atmosphere. Prevalent concepts include flapping wings that mimic birds or insects and rotating, lifting rotors. The dominant aerodynamics for these vehicles involves highly unsteady, dynamic-stall, vortex-driven flows. The lifting capability of state-of-the-art flapping-wing vehicles is too low. This Challenge seeks to enhance dynamic lift through different concepts that might involve reflexive wing structures, flow-energy extraction, and active flow control. This will require physics-based flow models and time-resolved experiments for highly unsteady flows to maximize lift, maneuverability, and flight control of these vehicles. Key milestones include

- Generate and validate time-resolved experimental data for highly unsteady low-Reynolds-number flows.
- Develop feasible approaches for flow-energy extraction and reflexive wing structures for small UAVs.

Relevance to Strategic Objectives

Capacity (1): This Challenge has no impact on this Objective.

Safety and Reliability (1): This Challenge has no impact on this Objective.

Efficiency and Performance (3): Some of the unsteady aerodynamics associated with this Challenge also applies to rotorcraft.

Energy and Environment (1): This Challenge has no impact on this Objective.

Synergies with National and Homeland Security (9): This Challenge addresses highly maneuverable autonomous flight in confined urban environments, which is relevant to the missions of DoD and DHS.

Support to Space (3): This Challenge is relevant to space missions involving aircraft in the martian atmosphere.

Why NASA?

Supporting Infrastructure (3): NASA has facilities in which to perform this research, although they are not unique.

Mission Alignment (9): This Challenge is very relevant to NASA s mission.

Lack of Alternative Sponsorship (3): DoD also supports relevant research, although flight in planetary atmospheres is only of interest to NASA.

Appropriate Level of Risk (9): This Challenge faces moderate risk; reasonable progress can be expected during the next decade of research.

A17 Low-drag airship designs to enable long-duration stratospheric flight

Airships capable of operating in the stratosphere for extended periods of time are being investigated for communications relay and surveillance applications. They offer the ability to provide wide area coverage from a persistent platform, while enabling economical retrieval of payloads for repair or replacement. These vehicles build on technologies available for existing airships that operate at lower altitudes, but require advances in lightweight hull fabrics, efficient energy generation and storage, low-drag aerodynamic configurations, and efficient propulsion systems capable of operation in a low-Reynolds-number environment.

Minimizing the drag of these vehicles is important, since a significant portion of the required onboard energy is expended by the propulsion system for station-keeping against winds. Aerodynamic issues of interest include boundary layer transition prediction for flexible thin-wall hulls, prediction of viscous drag in the regions of turbulent flow, boundary layer separation control, and unsteady aerodynamics associated with gossamer structures. Key milestones include

- Develop techniques for prediction of boundary layer transition in unsteady flows.
- Develop coupled aerodynamic and structural analysis tools for predicting the aerodynamics associated with deformable vehicles.

Relevance to Strategic Objectives

Capacity (1): This Challenge has no impact on this Objective.

Safety and Reliability (3): Stratospheric airships may provide persistent surveillance of low-flying aircraft or weather patterns, but the expected impact on this Objective is limited.

Efficiency and Performance (1): This Challenge has no impact on this Objective.

Energy and Environment (3): This Challenge could enhance environmental sensing.

Synergies with National and Homeland Security (9): The development of efficient and affordable stratospheric airships will provide a new class of vehicle for providing persistent surveillance and communication relay. Both DoD and DHS are investigating high-altitude airships for these applications.

Support to Space (1): This Challenge has no impact on this Objective.

Why NASA?

Supporting Infrastructure (3): NASA has both computational and experimental tools relevant to the development of airship technology. DoD and industry are capable of contributing infrastructure as well.

Mission Alignment (3): Development of fundamental technologies for gossamer vehicles is very relevant to NASA s mission.

Lack of Alternative Sponsorship (3): Both DoD and DHS are currently investing in the relevant technologies.

Appropriate Level of Risk (9): This Challenge faces high risk, but significant progress in understanding the underlying limitations of the technology could be made within the next 10 years.

A18 Prediction of communication capability through reentry trajectory and techniques to mitigate impact of communication blackouts

Vehicles returning from space through the atmosphere will encounter regions where communication is greatly reduced and at times nonexistent due to interaction with the atmosphere. At hypersonic velocities, aerothermal stresses create a charged flow field around the vehicle, eventually eliminating communication through this highly charged shear layer. Maintaining continuous communication with these vehicles is important for accurate control, targeting, and continuous health monitoring. As hypersonic concepts move to flight experimentation, robust communication with test vehicles will be increasingly important for the test range to have adequate control, destruct authority, and capability to download sufficient data throughout the flight regime.

Research is needed to understand and characterize the shear and boundary layers, and the relationship between signal transmission and the flow physics. Several promising concepts are under investigation for minimizing the effects of this charged flow field, creating innovative designs and providing information through test and analysis.

Currently, communication blackout is tolerated and systems have been designed around this problem by accepting a ballistic trajectory until communication is restored. Several technologies have been demonstrated in limited capacity on the ground and in flight but not one has completely alleviated the problem. Key milestones include

- Improve computational tools for predicting electron number density around 3-D shapes in hypervelocity flows.
- Develop sharp-leading-edge technology to minimize electron production in stagnation regions.

Relevance to Strategic Objectives

Capacity (1): This Challenge has no impact on this Objective.

Safety and Reliability (1): This Challenge has no impact on this Objective.

Efficiency and Performance (1): This Challenge has no impact on this Objective.

Energy and Environment (1): This Challenge has no impact on this Objective.

Synergies with National and Homeland Security (9): This Challenge is relevant to DoD strategic and strike systems.

Support to Space (9): This Challenge is relevant to space exploration and specifically reentry from space.

Why NASA?

Supporting Infrastructure (3): NASA possesses relevant capabilities in hypersonics, but relevant assets exist in DoD as well.

Mission Alignment (9): This Challenge is very relevant to NASA s mission.

Lack of Alternative Sponsorship (3): Both NASA and DoD conduct research associated with improvements in reentry physics.

Appropriate Level of Risk (3): This Challenge faces very high risk.

A19 Aircraft protective countermeasures based on a range of small deployed air vehicles

This Challenge deals with the special aerodynamic issues associated with small subsonic or supersonic flight vehicles that might be deployed from commercial aircraft as a countermeasure to an attack from ground- or aircraft-launched missiles. The vehicles need to be highly maneuverable, autonomous, able to station-keep long enough to allow the passenger aircraft to escape the airspace, and inexpensive enough to be adopted by a wide range of civil aircraft. Relevant technologies include flow control approaches for flight control in subsonic (and, perhaps, supersonic) regimes. Possible vehicle configurations include small missile bodies and miniature delta-wing aircraft. Achieving maximum flight control will be critical and may involve advanced flow controls that manipulate coherent vortices and shock waves to produce large asymmetric surface pressure loading and resultant force vectoring. Key milestones include

- Develop validated techniques for deployment of small, lightweight vehicles from larger aircraft.

- Design novel aerodynamic configurations for small missile defense vehicles.

Relevance to Strategic Objectives

Capacity (1): This Challenge has no impact on this Objective.

Safety and Reliability (3): This Challenge would enhance safety and reliability in the face of a terrorist attack.

Efficiency and Performance (1): This Challenge has no impact on this Objective.

Energy and Environment (1): This Challenge has no impact on this Objective.

Synergies with National and Homeland Security (9): This Challenge enables highly maneuverable, autonomous flight vehicles that have national and homeland defense applications.

Support to Space (1): This Challenge has no impact on this Objective.

Why NASA?

Supporting Infrastructure (3): NASA has facilities that can perform this research, although they are not unique.

Mission Alignment (3): This Challenge is relevant to NASA s mission.

Lack of Alternative Sponsorship (3): DoD already supports relevant R&T, although it is focused on protecting military aircraft.

Appropriate Level of Risk (3): This Challenge faces low risk.

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B

R&T Challenges for Propulsion and Power

A total of 16 R&T Challenges were prioritized in the propulsion and power Area. Table B-1 shows the results. The R&T Challenges are listed in order of NASA priority. National priority scores are also shown.[1] This appendix contains a description of each R&T Challenge, including milestones and an item-by-item justification for each score that appear in Table B-1.[2]

B1a Quiet propulsion systems

The adverse environmental by-products of aviation—primarily noise and emissions—are major constraints on the growth of aviation. Public concerns over the environmental impact of aircraft and airport operations, along with increasingly strict legal and regulatory requirements, can severely constrain the ability of civil aviation to meet national and global needs for mobility, increased market access, and sustained economic growth. Aircraft noise concerns include takeoff and landing noise; taxi and engine run-up noise; flyovers at cruise altitude over very quiet areas; and sonic booms associated with supersonic flight.

Figure B-1 shows how the impact of aviation noise on people living around airports has declined in the United States. It contrasts the growth of air travel with the reduction in the number of people exposed to 65-decibel (dB) day-night average sound level (DNL), which is what the federal government has defined as the "significant noise level." In 1975, approximately 7 million people were exposed to significant aircraft noise. Since 1975, the number of persons exposed to significant noise levels has greatly declined even as air travel has grown dramatically. One of the most effective federal policies implemented to reduce aviation noise was the transition of commercial aircraft to quieter models. The availability of low-noise technologies, such as high-bypass-ratio engines, contributed significantly to this transition.

Assuming the industry s continued recovery, and given the goal of doubling capacity over the next 10 to 35 years, future abatement efforts may need to achieve noise levels, as recognized by authorities both in the United States (NASA, 2003) and Europe (ACARE, 2001). The environmental impact of aircraft noise is projected to remain roughly constant in the United States for the next several years and then increase as air travel growth outpaces expected technological and operational advancements (Waitz et al., 2004). Furthermore, the public currently reports considerable annoyance even when DNLs are below 65 dB. Regulatory actions to limit or reduce noise exposure will likely lead to even more stringent limits.

Meeting future noise targets will be extremely challenging and will require continued fundamental research in noise generation and transmission phenomena and advanced propulsion technologies. Since the revolutionary introduction of the turbofan, engine source noise reductions have been more evolutionary, with incremental advances such as high-bypass-ratio engines and better acoustic liner technology. The development of validated noise prediction tools by NASA will greatly aid the development of quieter engines. NASA should emphasize physics-based noise source models that can distinguish core noise from other engine noise sources to identify source mechanisms. Research is needed to reduce the noise of engine systems, including fan noise, jet noise, and core noise. Research should also encompass systems analysis; advanced concepts, such as adaptable chevrons; the community impact of aircraft noise; and improved metrics to quantify and mitigate these impacts.

Noise and emissions are not independent phenomena in aircraft engines. There are physical interrelationships between noise and emissions and among various types of emissions, so that when one is decreased, another may be increased.

[1] The prioritization process is described in Chapter 2.

[2] The technical descriptions for the first 10 Challenges listed below contain substantially more detail than the technical descriptions for these Challenges as they appear in Chapter 3.

TABLE B-1 Prioritization of R&T Challenges for Area B: Propulsion and Power

R&T Challenge		Strategic Objective: Capacity	Strategic Objective: Safety and Reliability	Strategic Objective: Efficiency and Performance	Strategic Objective: Energy and the Environment	Strategic Objective: Synergies with Security	Strategic Objective: Support to Space	National Priority	Why NASA?: Supporting Infrastructure	Why NASA?: Mission Alignment	Why NASA?: Lack of Alternative Sponsors	Why NASA?: Appropriate Level of Risk	Why NASA Composite Score	NASA Priority Score
	Weight	5		3		1			1/4 each					
B1a	Quiet propulsion systems	9	1	3	9	3	1	**90**	3	9	3	9	**6.0**	**540**
B1b	Ultraclean gas turbine combustors to reduce gaseous and particulate emissions in all flight segments	9	1	3	9	3	1	**90**	3	9	3	9	**6.0**	**540**
B3	Intelligent engines and mechanical power systems capable of self-diagnosis and reconfiguration between shop visits	3	9	3	3	3	1	**82**	3	9	3	9	**6.0**	**492**
B4	Improved propulsion system fuel economy	3	1	9	9	3	1	**78**	3	9	3	9	**6.0**	**468**
B5	Propulsion systems for short takeoff and vertical lift	9	1	3	3	3	1	**72**	3	9	3	9	**6.0**	**432**
B6a	Variable-cycle engines to expand the operating envelope	3	1	9	3	3	9	**68**	3	9	3	9	**6.0**	**408**
B6b	Integrated power and thermal management systems	3	1	9	3	3	9	**68**	3	9	3	9	**6.0**	**408**
B8	Propulsion systems for supersonic flight	3	1	3	1	9	9	**50**	9	9	3	9	**7.5**	**375**
B9	High-reliability, high-performance, and high-power-density aircraft electric power systems	1	3	9	3	3	3	**62**	1	9	3	9	**5.5**	**341**
B10	Combined-cycle hypersonic propulsion systems with mode transition	1	1	3	1	9	9	**40**	9	9	3	9	**7.5**	**300**
B11	Alternative fuels and additives for propulsion that could broaden fuel sources and/or lessen environmental impact	3	1	3	9	3	1	**60**	3	3	3	9	**4.5**	**270**
B12	Hypersonic hydrocarbon-fueled scramjet	1	1	3	1	9	9	**40**	9	3	3	9	**6.0**	**240**
B13	Improved propulsion system tolerance to weather, inlet distortion, wake ingestion, bird strike, and foreign object damage	3	9	3	1	3	1	**76**	3	3	3	3	**3.0**	**228**
B14	Propulsion approaches employing specific planetary atmospheres in thrust-producing chemical reactions	1	1	1	1	1	9	**26**	3	9	9	9	**7.5**	**195**
B15	Environmentally benign propulsion systems, structural components, and chemicals	1	1	1	9	3	1	**44**	3	3	3	3	**3.0**	**132**
B16	Reduced engine manufacturing and maintenance costs	3	3	3	3	3	1	**52**	3	1	1	3	**2.0**	**104**

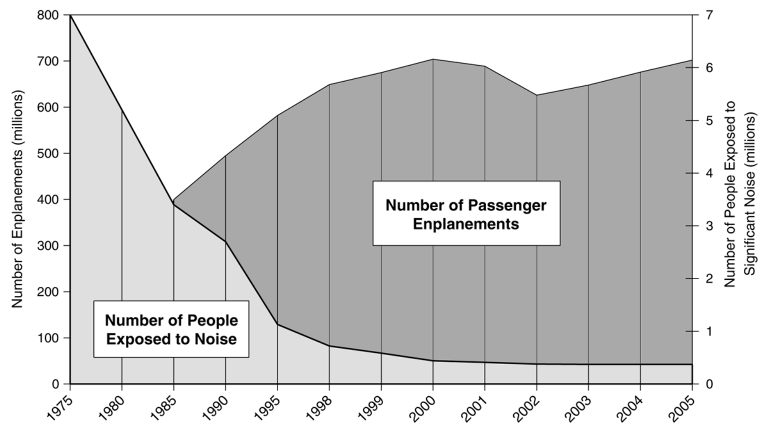

FIGURE B-1 Actual and predicted exposure to significant noise (65-dB day-night average sound level) and enplanement trends for the United States, 1975-2005. SOURCE: C. Burleson, FAA, "Aviation environmental challenges," Presentation to Panel B on December 13, 2005.

Adequately understanding and mitigating the environmental impact of aviation requires an integrated approach to noise and emissions research that considers these tradeoffs.

High-risk, long-term research is required to meet future demands. Close collaboration between government and industry is required to mature and transition promising technologies. NASA plays a critical role in supporting fundamental source noise abatement research at universities, which can lead to both revolutionary technology advances and a workforce that can answer new technical questions. Key milestones include

- Develop validated physics-based models to predict engine noise and conduct trade-off studies.
- Improve understanding and prediction capabilities, and develop propulsion cycles compatible with noise and emissions reduction.
- Develop advanced low-noise fan designs, liner concepts, and active control technologies.
- Develop concepts to reduce installed noise (e.g., adaptable chevrons).
- Develop and demonstrate propulsion designs that show the feasibility of technologies to reduce noise by 10 dB (in 15 years) from Boeing 777/GE 90 levels.

Relevance to Strategic Objectives

Capacity (9): In the absence of breakthroughs, increasingly strict noise requirements will constrain aviation system capacity.

Safety and Reliability (1): This Challenge will not help to achieve this objective, though equipment designed to reduce noise must be compatible with safety and reliability requirements.

Efficiency and Performance (3): Some noise reduction approaches (e.g., higher bypass ratio) increase efficiency while others (e.g., acoustic liners) increase weight, which may reduce efficiency. In addition, engines often run at nonoptimal conditions to reduce noise. Innovative noise solutions may permit new, optimized operating approaches.

Energy and the Environment (9): Aircraft noise directly impacts the environment.

Synergies with National and Homeland Security (3): Noise constraints impact DoD operations in civil airspace. This Challenge will alleviate this constraint.

Support to Space (1): This Challenge has no impact on this Objective.

Why NASA?

Supporting Infrastructure (3): NASA is well poised to conduct engine source noise abatement research. It has excellent facilities, a large staff of qualified personnel working in this area, and a track record of contributing to advancements. However, strong capabilities also exist at universities and in industry.

Mission Alignment (9): This Challenge is very relevant to NASA s mission to improve aircraft performance.

Lack of Alternative Sponsors (3): NASA is well-qualified to support this Challenge, but industry has a strong incentive to conduct noise reduction research, even if NASA does not.

Appropriate Level of Risk (9): This Challenge is high risk.

B1b Ultraclean gas turbine combustors to reduce gaseous and particulate emissions in all flight segments

Emissions from aircraft constrain the growth of aviation due to their environmental impacts and potential human health consequences. While aviation sources remain a very small percentage of transport emissions, local worries about the environmental impact of these emissions can impede airport improvements to increase capacity. About 25 percent of U.S. commercial airports are in areas that are in nonattainment or maintenance for national ambient air quality standards—including 43 of the top 50 airports. Airports located in air quality nonattainment or maintenance areas increasingly find that air emissions add to the complexity, length, and uncertainty of the environmental review and approval of expansion projects (Akin et al., 2003). Furthermore, it is increasingly difficult for airport development projects to conform to Clean Air Act requirements, and air quality regulators in some states are working to directly or indirectly control growing aircraft emissions.

Key pollutants of concern include oxides of nitrogen and sulfur (NO_x and SO_x), carbon monoxide (CO), unburned hydrocarbons (UHCs), hazardous air pollutants, and particulate matter (PM). In addition, emissions of carbon dioxide (CO_2) and water vapor (H_2O) in the upper troposphere and stratosphere are of concern because of their potential impact on Earth s climate (IPCC, 1999). Both CO_2 and H_2O are inherent combustion products of hydrocarbon fuels, and their emissions can only be reduced through improvements in overall cycle efficiency (see R&T Challenge B4) or a change in fuels.

Emissions of SO_x and, possibly, PM can be reduced through fuel processing (e.g., desulfurization), fuel additives, or both. However, an improved understanding of PM formation and destruction mechanisms is required to reduce PM emissions. This a difficult problem given the inherent chemical complexity of aviation jet fuels and the lack of well-validated measurement techniques for PM.

Emissions of NO_x, CO, UHC, and PM from the combustor can be reduced through the development of ultraclean combustion approaches, a critical step to mitigate the environmental impacts of aviation. Understanding (1) the tradeoffs between different emissions and noise and (2) the health and welfare impacts of various emissions and noise at different levels is also necessary to make informed design choices.

Low NO_x emissions can be achieved with both lean-burning combustor designs and those that run rich in the front end (but lean overall)—the main point being low combustion temperatures. In addition, catalytic combustion systems have ultralow emissions levels, but durability and cost considerations make them unlikely candidates for aviation applications, at least for several decades. Rich-burn concepts (such as the so called rich-burn/quick-quench/lean-burn concept) use sequential rich, then lean combustion and, to some extent, are realized in most commercial engines using a rich primary zone followed by dilution. Key technical issues with this concept involve PM emissions and quench zone mixing (Lefebvre, 1999). Lean combustion concepts attempt to create a lean premixed fuel-air mixture, either upstream of the combustion chamber with lean, premixed, prevaporized (LPP) designs, or in the combustion chamber with multipoint, lean direct injection (LDI) approaches. Lean premixed approaches have received substantial market penetration in land-based gas turbine applications over the last two decades. While the majority of these devices use natural gas, similar LPP concepts have been used for liquid fuels by vaporizing the fuel. Such systems have demonstrated ultralow levels of NO_x, CO, UHC, and PM. The key issues associated with LPP combustors are unsteady combustion phenomena, including combustion instability, flame blow-off, flashback, and autoignition, which are major operability concerns; autoignition is a key concern in high-pressure-ratio engines. These unsteady combustion issues are prominent concerns in commercial land-based applications and have degraded engine reliability and availability relative to more polluting alternatives (i.e., non-premixed flame combustors). LDI approaches, which have been extensively explored at NASA, avoid flashback and autoignition, but at the price of increased complexity. A variant of these concepts is to heavily dilute the fuel-air mixture with combustion products prior to combustion, sometimes referred to by the misnomer flameless combustion.

These combustion approaches share a number of common issues that should form the basis of future NASA research. These include mixing, PM formation and inhibition, and unsteady combustion phenomena. Fast, effective fuel-air and combustion product–reactant–quench air mixing is a key enabling technology for all of the above-mentioned combustion technologies. Unsteady combustion phenomena are quite complex and, while heuristic explanations have allowed for an understanding of the basic physics, more in-depth understanding of the underlying dynamic processes is required to develop true predictive capabilities. For example, the conditions under which combustion instabilities occur and the amplitudes of instabilities cannot currently be predicted. In addition, some phenomena, such as blowoff or flashback, are well understood in fundamental laboratory burners but not at all in practical swirling devices, where new mechanisms and physics occur.

Developing effective mitigation for PM is predicated on understanding the formation of particles and their composition, growth, and transport mechanisms. Effective measurement techniques are also needed to assess aviation s contribution to PM concentrations and potential interrelationships between PM and other aviation emissions, as well as noise. Metrics for human health and atmospheric impacts should also be established and correlated with particulate emissions from aviation. Finally, mitigation strategies to address all aviation emissions, taking into account interdependencies, need to be defined and developed. Key milestones include

- Understand PM formation mechanisms and kinetics and develop fuel additives to disrupt formation.
- Understand air toxicity measurement techniques and the impact of PM on human health and welfare.
- Improve understanding and prediction capabilities and develop optimized approaches for mixing in multiphase flows.
- Develop large eddy simulations (LES) with optimized subgrid models that contain key physics needed to capture chemical reactions, mixing, and unsteady combustor phenomena.
- Develop physics-based, reduced-order combustor models, including emissions, combustion instability, blowoff, and flashback, for inclusion in intelligent engine control systems.
- Develop validated chemical mechanisms that describe fuel kinetics.
- Develop and demonstrate combustor designs that show the feasibility of technologies to reduce NO_x emissions by 85 percent while also reducing PM, relative to 1996 International Civil Aviation Organization (ICAO) limits for future large and regional subsonic engines (with pressure ratios of 55:1 and 30:1, respectively).

Relevance to Strategic Objectives

Capacity (9): This Challenge will help create breakthroughs that are necessary to prevent increasingly strict emissions requirements from constraining the capacity of the air transportation system.

Safety and Reliability (1): Reliability issues have been a prominent issue for commercialized low-emissions combustors for ground-based applications. Low-emission combustion approaches for aircraft engines are unlikely to enhance safety and need to be well engineered so safety and reliability are not compromised.

Efficiency and Performance (3): Efficiency improvements reduce the fuel burn and pollutants emitted for a given mission, all other things remaining equal.

Energy and the Environment (9): Combustor emissions directly impact the environment.

Synergies with National and Homeland Security (3): Improved understanding of dynamic combustion processes and mixing will contribute to DoD goals for main engine and augmentor combustors.

Support to Space (1): This Challenge has no impact on this Objective.

Why NASA?

Supporting Infrastructure (3): NASA has excellent facilities and a large staff working in this area, but strong capabilities also exist at other university, DoD, and DOE laboratories.

Mission Alignment (9): This Challenge is very relevant to NASA s mission to improve aircraft performance.

Lack of Alternative Sponsors (3): NASA is well qualified to support this Challenge, but DOE and DoD are also supporting similar programs for power, energy, and military applications.

Appropriate Level of Risk (9): This Challenge is quite challenging.

B3 Intelligent engines and mechanical power systems capable of self-diagnosis and reconfiguration between shop visits

In the future, advances in sensing, control, and information technology will lead to engines that are more sophisticated and more intelligent. Research thrusts should investigate how more intelligent systems can (1) improve engine health diagnostics and remedial actions in flight, (2) optimize the mission, and (3) use flight data to improve maintenance on the ground.

For current engines, the focus will be very much on diagnostics. Better physics-based modeling will be essential. Development of better CFD tools, better life-prediction tools, and better performance, steady-state, and dynamic checks will be the keys to success. Reducing in-flight shutdowns by a factor of 3 and unscheduled engine removals and delays and cancellations by a factor of 5 should reduce maintenance costs by 50 percent. Requirements include (1) smaller sensors, with better response and higher operating temperatures and (2) better materials with narrower properties tolerances. This should increase the lives of disks and airfoils by 50 percent.

Intelligent engine development will include active combustor control, which will permit operation with leaner burners, leading to lower NO_x emissions. Active stall control will enable compressors at higher pressure ratios, increasing propulsion efficiency. For engines with current architectures, intelligent engines will put more emphasis on variable systems. The goal will be to have an engine morph itself between takeoff and cruise, for example, to accommodate the individual point requirements. On new engines with new architectures, the ultimate intelligent engines will be the variable-cycle engines, which are discussed in Challenge B6a below.

Another technology to develop will be closed-loop clearance control. A pressing need in this regard is the development of a three-point probe system to monitor turbine clearances online. Software will be developed to control turbine clearances by modulating the cooling air on the casing. In-service deterioration will be reduced by accommodating the clearance loss due to rubs in the airfoils and the casing and by minimizing large clearances due to transients. This should significantly reduce operating temperature margins. Reducing the required engine margins by 50°F would increase on-wing life by about 3 years for most engines. Such a system would improve turbine efficiencies in flight and reduce fuel burn as much as 2 percent. Other relevant technologies include variable exhausts, active cooling control, improved aircraft–engine integration, better electric power generation, and better noise and emissions controls. Key milestones include

- Develop better computational simulation tools to understand operability limits.
- Develop better life prediction tools.
- Develop improved steady-state and dynamic performance checks.
- Develop improved health diagnostics systems.
- Develop new health prediction systems.
- Develop improved clearance control systems.
- Develop active compressor stall control.
- Develop active combustion control.

Relevance to Strategic Objectives

Capacity (3): Intelligent engines can improve capacity by preventing in-flight shutdowns and reducing delays and cancellations caused by unscheduled maintenance.

Safety and Reliability (9): Intelligent engines will provide new diagnostics systems and life-prediction capabilities that will greatly improve aviation safety and reliability.

Efficiency and Performance (3): Intelligent engines will help increase efficiency by reducing aircraft downtime, and they may provide a small reduction in fuel burn through engine optimization.

Energy and the Environment (3): Intelligent engine technology may reduce engine noise or control combustion for lowered pollutant formation.

Synergies with National and Homeland Security (3): This Challenge is relevant to military aircraft.

Support to Space (1): Space propulsion systems are generally highly instrumented so contributions from intelligent engine technology are likely to be minor, particularly for expendable vehicles.

Why NASA?

Supporting Infrastructure (3): NASA has very good sensor development and modeling capabilities.

Mission Alignment (9): This Challenge is very relevant to NASA s mission to increase aircraft performance and operability.

Lack of Alternative Sponsors (3): This Challenge involves far-reaching technology that industry expects NASA to develop. DoD and DOE also perform relevant research.

Appropriate Level of Risk (9): This is challenging research that requires breakthroughs to succeed.

B4 Improved propulsion system fuel economy

The fuel economy of gas turbine propulsion systems is a function of engine efficiency, propulsion-induced drag, and propulsion weight. Overall engine efficiency is the product of the efficiency of creating hot, high-pressure gases (thermal or cycle efficiency), the efficiency of transferring energy from the hot high-pressure gases to a more desirable form (transfer efficiency), and the efficiency of creating thrust from the engine fan and core flows (propulsion efficiency). The thermal efficiency for a gas turbine (Brayton cycle) is primarily a function of the overall engine pressure ratio. That is, as long as the turbine can tolerate the inlet temperature corresponding to a given pressure ratio, the overall pressure ratio sets the efficiency of the cycle. Figure B-2 illustrates very clearly that state-of-the-art gas turbines have not reached the theoretical limits of thermal efficiency. The technologies identified in the figure have the potential to improve the thermal efficiency of gas turbines, to significantly increase fuel economy, and to decrease the environmental impact of the air transportation system.

The pressure ratio for state-of-the-art gas turbines is approximately 46:1 (for large engines) and 18 to 1 (for small engines). To reach fuel economy goals, the overall pressure ratios for large engines must be increased to between 60:1 and 65:1, and small engines must be increased to between 30:1 and 40:1. The technology that limits the overall pressure ratio is compressor disk material stress at operating temperature. Maximum disk temperature must be increased from 1350°F to 1500°F, and turbine blade materials, coatings, and cooling configurations must withstand 3600°F. Thus, advances in materials technology are key enablers of enhanced fuel economy.

Transfer efficiency is determined by the component efficiencies of the fan and low-pressure turbine and the losses of

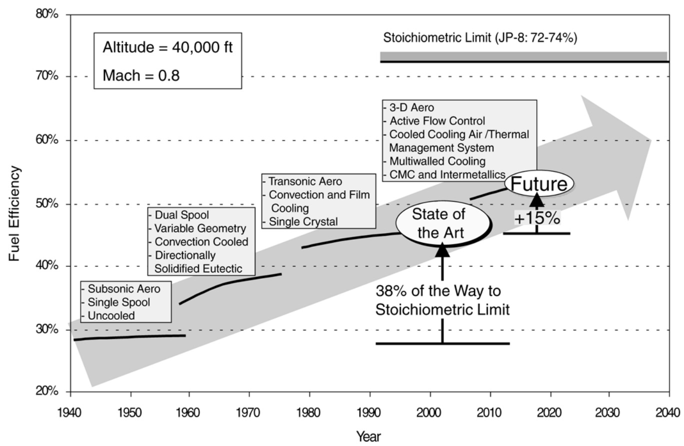

FIGURE B-2 Considerable gas turbine fuel efficiency improvements are still possible. SOURCE: J. Stricker, Air Force Research Laboratory, Private communication to panel member D. Crow, February 2006.

the shaft bearings. High-efficiency, low-pressure turbines need high rotor speeds, but highly efficient fans require low rotor speeds. Therefore, engines with high transfer efficiency must have reduction gearboxes or other technologies that permit different rotor speeds for the fan and low-pressure turbine.

Propulsion efficiency is a function of the difference between the velocity of engine exhaust and the forward velocity of the aircraft. Increasing the mass flow of air through the system at slower speed improves propulsion efficiency and decreases noise. However, doing so increases the diameter of the engine, which increases friction and flow blockage. Since larger engines will also be heavier, the use of composites or other lightweight materials for construction of the large structural pieces of the turbofan will also be necessary.

As shown in Figure B-2, improving thermal efficiency by 15 percent requires advances in several technologies: 3-D aerodynamics, active flow control, cooled cooling air and a thermal management system, multiwalled cooling, and ceramic matrix composites (CMCs) and intermetallics. Also, unconventional engine architectural arrangements, such as unducted fan engines, have demonstrated high performance potential and should be considered.

Over the long term, advances in all three efficiencies (thermal, transfer, and propulsion) should be able to improve fuel economy by 30 percent relative to the GE 90 for large commercial engines and 30 percent relative to T700/CT7 for small engines. Key milestones include

- Demonstrate laboratory-scale materials for 1500°F compressor disks.
- Demonstrate materials for full-scale, 1500°F compressor disks.
- Perform 1,000-hour test of a 50-horsepower per pound speed reduction gearbox.
- Test a reduced-weight, high-bypass-ratio engine and nacelle-to-wing configuration in a wind tunnel.
- Demonstrate an acceptably low-cost, advanced high-pressure turbine cooling system.

Relevance to Strategic Objectives

Capacity (3): Improving the fuel economy of civil aircraft will reduce operating costs and increase capacity by permitting airlines to increase flight schedules and fleet sizes profitably.

Safety and Reliability (1): This Challenge has no impact on this Objective.

Efficiency and Performance (9): The fuel economy of the propulsion system and the drag of the aircraft determine the fuel burned for air travel. Based on FAA projections (FAA, 2006), a 20 percent increase in fuel economy would decrease fuel consumption by U.S. civil aviation by 4 to 6 billion gallons a year between 2006 and 2016. As gas prices approach $2 per gallon, this amounts to $8 billion to $12 billion dollars.

Energy and the Environment (9): Increasing fuel economy will significantly decrease aircraft emissions. Also, because increasing fuel economy requires engines with higher bypass ratios, it will also decrease noise.

Synergies with National and Homeland Security (3): Increasing fuel economy in civil aircraft will require engines that operate at higher pressure ratios. The high-pressure engine core is applicable to military aircraft engines.

Support to Space (1): This Challenge has no impact on this Objective.

Why NASA?

Supporting Infrastructure (3): NASA programs such as the Energy Efficient Engine and the High Speed Civil Transport have led to technologies that have greatly improved civil aviation. NASA has the complete set of analytical and experimental tools to undertake this Challenge, including excellent staff and facilities for the development of gearboxes. However, DoD and industry also have many of the necessary tools.

Mission Alignment (9): This Challenge is very relevant to NASA s mission.

Lack of Alternative Sponsors (3): No organization other than NASA is supporting high-bypass-ratio research to improve fuel economy. However, DoD is supporting research to increase overall engine pressure ratio.

Appropriate Level of Risk (9): Relevant R&T related to materials and rotating machinery aerodynamic issues faces significant risk.

B5 Propulsion systems for short takeoff and vertical lift

The use of short (STOL), extremely short (ESTOL), or vertical (VTOL) takeoff and landing airplanes (collectively called V/STOL)[3] and increased use of helicopters could greatly increase the capacity of the air transportation system by allowing more takeoffs and landings at existing airports without increasing demand for runway usage (NRC, 2003). V/STOL airplanes include tilt-wing aircraft, tilt-rotor aircraft, vertical-lift fan aircraft, and blown-wing aircraft.[4] Currently, the fuel economy of V/STOL propulsion systems is not on par with that of fixed-wing commercial airplanes. Propulsion systems for all new aircraft must also demonstrate extremely high levels of reliability. Propulsion systems for V/STOL aircraft are in an early state of development or do not exist for civil airplanes. In addition, engine-out strategies need to be developed and verified for certification.

This Challenge should support development of V/STOL and helicopter propulsion systems with fuel economy comparable to future small commercial aircraft—namely, 20 percent better than the CT7 family of engines that is currently in production for small conventional aircraft. Many of the same technologies that apply to large and small engines for conventional aircraft also apply to V/STOL propulsions systems. However, additional technologies such as high-efficiency, angled gearboxes; high-efficiency reduction gearboxes, large-bleed systems; thrust vectoring systems; noise reduction both inside and outside the aircraft; and fan-tip-driven turbines will be required to put V/STOL airplanes into affordable, large-scale commercial service with minimal environmental impact.

There are three major technology efforts to be undertaken in support of V/STOL aircraft for civil aviation. The most important is to demonstrate an engine in the 3,000-shaft-horsepower (hp) range that meets the fuel economy goals. The important characteristics of this demonstration engine are to achieve overall pressure ratios of 25:1 or 30:1 and turbine inlet temperatures of 2800°F. This will require some combination of the following technologies: (1) new compressor disk materials, (2) greatly improved turbine cooling configurations, (3) new turbine blade alloys and coatings, (4) component aerodynamics designed with the latest computational models, and (5) highly effective, low-pressure-drop dirt separation devices. Such an engine would benefit helicopters as well.

Secondly, the powertrain system of most V/STOL airplanes (as well as helicopters) will consist of shafting with speed reduction gearboxes, angled gearboxes, and perhaps clutch systems. Reliable clutch operation would enable many new types of V/STOL aircraft. NASA should develop the design tools and demonstrate candidate gearboxes and clutch systems.

Thirdly, engine-assisted wing lift, such as the blown wing, offers the simplest, most energy-efficient short takeoff. Wing aerodynamics need to be developed and the bleed or suction

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[3]VTOL airplanes can take off and land vertically. They include tilt-rotors, the AV-8 Harrier, and the JSF. VTOL airplanes do not routinely take off or land vertically because of the range-payload penalty associated with the weight limitations of purely vertical operations. Rather, they use any available field length to develop some forward motion and wing lift during takeoff to increase the useful load (fuel plus payload). They tend to land vertically only at the end of the mission, when they are lighter, after burning fuel and/or dropping weapons.

STOL airplanes use high-lift systems to take off in less distance than conventional aircraft (typically a few thousand feet). Very few STOL aircraft can safely take off on runways shorter than 3,000 ft and none on runways less than 2,000 feet. (This class does not include ultralight aircraft, kit planes, etc. that can operate out of short fields due to their small size but do not have high-lift system.)

ESTOL airplanes would be able to safely take off on runways of 2,000 ft. They would have high-lift systems and thrust-to-weight ratios that are higher than conventional aircraft but not as high as VTOL aircraft. ESTOL aircraft have not yet been developed for commercial or military operations.

V/STOL refers to both VTOL and STOL airplanes that convert to fixed-wing flight after takeoff; it does not include helicopters.

[4]Blown-wing V/STOL aircraft use engine exhaust directed to specific locations on the wing to increase lift during takeoff and landing.

locations and quantities required need to be demonstrated for blown-wing V/STOL airplanes.

The tools, techniques, and devices demonstrated in the paragraphs above would enable new families of V/STOL aircraft to enter the civil aviation market. The capabilities of these aircraft would greatly increase the capacity of the civil air transportation system and decrease door-to-door travel time for the flying public. Key milestones include

- Demonstrate pressure ratios between 25:1 and 30:1 and turbine inlet temperatures of 2800°F for 3,000-shaft-hp-class engine components.
- Develop and validate the design tools required for candidate gearboxes and clutch systems.
- Demonstrate highly reliable gearboxes, which have transfer efficiencies of about 99.8 percent and power: weight ratios of about 50 hp per pound.
- Demonstrate clutch system technologies with 10,000-cycle life and a probability of failure of 1×10^{-6} over the life of the system.

Relevance to Strategic Objectives

Capacity (9): V/STOL civil airplanes would allow more takeoffs and landings at existing airports and enhance the role of small or regional airports within the air transportation system.

Safety and Reliability (1): New V/STOL aircraft would be certified for commercial use only if they meet the existing high standards for safety and reliability. For vertical lift approaches, engine out strategies need to be demonstrated and validated. Congestion relief could increase safety.

Efficiency and Performance (3): Efficient V/STOL civil airplanes will decrease door-to-door travel time.

Energy and the Environment (3): Properly designed and engineered V/STOL airplanes could help restrict noise to within the boundaries of the airport, but they might increase noise within airport boundaries.

Synergies with National and Homeland Security (3): DoD and DHS have used and will continue to use many V/STOL airplanes.

Support to Space (1): This Challenge has no impact on this Objective.

Why NASA?

Supporting Infrastructure (3): NASA has many analytical and experimental tools to develop propulsion systems for V/STOL airplanes. DoD also has some relevant tools. In the past, NASA and the Army shared funding and leadership in basic rotorcraft research. However, NASA eliminated all rotorcraft funding in FY 2006.[5]

[5]R. Flater, American Helicopter Society, Letter to Curt Weldon, Chairman, Tactical Air and Land Forces Subcommittee, U.S. House of Representatives Committee on Armed Services, February 18, 2005. Contained in an appendix to NIA (2005).

Mission Alignment (9): This Challenge is very relevant to NASA s mission.

Lack of Alternative Sponsors (3): DoD will develop some—but not all—of the technologies needed by civil V/STOL airplanes.

Appropriate Level of Risk (9): Propulsion technology required to develop affordable and environmentally benign civil V/STOL airplanes does not yet exist.

B6a Variable-cycle engines to expand the operating envelope

Variable-cycle engines have two or three flow paths through the engine, variable vanes, and variable exhaust nozzles, all of which allow them to vary engine bypass ratios and pressure ratios. Variable-cycle engines can improve the performance of both military and civil aircraft in many flight regimes by changing the bypass ratio and pressure ratio as a function of speed, altitude, and mission requirements. For the long-range JSF, this should permit a twofold increase in rapid response radius, an eightfold increase in loiter capability, and a 30 percent reduction in gross weight. For a JSF follow-on aircraft, a 25 percent increase in lift and a 10-25 percent increase in range, depending on the mission, appear possible.

Variable-cycle engines have the potential to increase subsonic engine fuel economy. They also appear attractive for a supersonic commercial aircraft that has to accommodate stringent takeoff noise requirements and still achieve reasonable performance at supersonic speeds. For access to space, variable-cycle engines could provide a large reduction in payload costs as well as marked safety improvements.

This Challenge will lower noise at takeoff while maintaining good fuel consumption at cruise, and it will enable optimized engine configurations during climb and descent. Engines will be able to run cooler, which will reduce maintenance costs.

This Challenge requires the development of numerous technologies: integrated thermal management approaches; reliable prime air-to-fuel heat exchangers; low-pressure-drop air-to-air heat exchangers; improved JP-8 heat sink capability; CMC technologies and associated life-prediction tools for operation above 2400°F; complex shape fabrication; high-speed bearings; improved turbine cooling; better engine health predictions; probabilistic life analysis; in-flight data analysis; low-emission, high-temperature combustors; variable-geometry fan systems; and improved airframe–engine integration. This Challenge would benefit from the development of smart engines (Challenge B3). Key milestones include

- Develop variable exhaust nozzle technology to optimize fuel burn.
- Develop improved thermal management systems.
- Develop CMC technologies for hot section components.
- Develop highly loaded, high-speed bearings.

- Develop probabilistic analysis for more accurate designs and life prediction.
- Develop improved turbine cooling technology.
- Develop high-temperature combustors to accommodate increased operating pressure ratios.
- Develop improved aircraft–engine integration tools.

Relevance to Strategic Objectives

Capacity (3): The reduced maintanence needed by these engines would decrease delays and increase availability.

Safety and Reliability (1): This Challenge has no impact on this Objective.

Efficiency and Performance (9): This Challenge will allow the aircraft to attain constant on-design performance by adapting to flight conditions.

Energy and the Environment (3): Variable-cycle engines may be able to tailor conditions to reduce noise or emissions, although they will primarily be used to improve performance and efficiency.

Synergies with National and Homeland Security (3): There will be some impact here as they will become our future weapon systems.

Support to Space (9): Variable-cycle engines are very relevant to potential two-stage-to-orbit systems.

Why NASA?

Supporting Infrastructure (3): NASA has relevant facilities in place, but they are not unique.

Mission Alignment (9): This Challenge is very relevant to NASA s mission, especially for supersonic systems and space.

Lack of Alternative Sponsors (3): Currently the only other agency that would sponsor relevant technologies would be DoD. Industry will not fund relevant R&T until it is more advanced.

Appropriate Level of Risk (9): This Challenge faces high risk.

B6b Integrated power and thermal management systems

The goal of this Challenge is to integrate and optimize, at the aircraft system level, the traditionally severable airframe power and thermal management system. An integrated systems approach optimizes aircraft cost, weight, and performance rather than optimizing individual components. This approach also enables integrated prognostics and health monitoring, thereby improving safety and reliability. The current state of the art involves architecture of federated systems, with separate component machinery for auxiliary and emergency power; environmental control; engine start; accessory drive units; waste heat rejection; and so on.

"Integration" refers to the physical, functional, and requirements integration of key propulsion and power system components, with those components combined into fewer multifunctional units all tied together in a more-electric architecture (see Challenge B9). Key components and functions include engine starting; electrical power generation, power conditioning, and routing; air cycle environmental control; avionics, fuel, and oil cooling; ventilation; flight control actuation; and overall vehicle and propulsion system thermal management, especially waste heat recovery and/or rejection. For example, engine start, auxiliary power, and environmental control systems may be combined into an airframe-mounted integrated power package that is physically coupled to the engine through power extraction and waste heat recovery. In this integrated approach, flight control systems are likely to be driven by electric or electrohydrostatic actuation, and thermal management is addressed in a seamless, system-level fashion. At the propulsion system level, electric power must be generated and integrated with airframe needs in the most efficient manner. This may be by a generator mounted on the shaft of the low-pressure turbine or, eventually, by fuel-cell-driven generators distributed within the airframe.

This Challenge includes airframe thermal management and waste heat recovery for higher speed applications. At hypersonic speeds, the thermal energy generated by the high-enthalpy flow over the airframe must be dissipated. The primary method for thermal management involves heating the fuel prior to combustion using structural cooling or heat exchange with working fluids used to cool the structure.

Today s modeling tools are derived from legacy approaches in which numerous component suppliers individually design, develop, and validate their product based on component-level requirements and specifications. New modeling and simulation infrastructures are necessary to allow these tools to be used in a system-level design framework, accommodating multiple platforms across multiple sites. A robust modeling framework is necessary to justify the system-level benefit of a given integrated component, which may need to weigh or cost more than a traditional component or have different or enhanced functionality.

Integrated systems also defy traditional business models in which hardware and software design, development, and validation responsibilities are clearly defined. In the integrated approach, some hardware manufactured or procured by the airframe manufacturer will be engine mounted, and some engine hardware may be mounted on the airframe. Although the engineering product is physically and functionally integrated, contractual responsibilities must still be divided between business units, and it is unclear how to do this. Key milestones include

- Identify and mature new business models for the design, development, validation, and support of hardware and software components of integrated systems.
- Develop an objected-oriented modeling infrastructure that allows networking resources to operate across different hardware platforms and geographic sites.

- Develop new engine-airframe systems integration architectures for both subsonic and higher speed flight.
- Develop physics-based subsystem component models that can analyze transient operations.
- Develop and mature concepts for the integration of fuel cell technology as secondary power sources.
- Develop advanced electric or electromechanical actuators that have rapid response, high power-to-weight, and low heat rejection.
- Develop subsystem components that can survive in more stressful thermal environments, require less cooling, and reject less waste heat, including thermally efficient fuel pumps and high-temperature electronics for power management and distribution systems.
- Develop lightweight, high-energy-density batteries.
- Develop advanced heat exchanger technologies.

Relevance to Strategic Objectives

Capacity (3): This Challenge will reduce aircraft weight and cost, increasing the number of passengers a given aircraft can carry.

Safety and Reliability (1): This Challenge will have little impact on system safety but should result in modest gains in system reliability.

Efficiency and Performance (9): This Challenge will significantly reduce fuel consumption, particularly with waste heat recovery rather than rejection.

Energy and the Environment (3): This Challenge will reduce emissions by increasing efficiency and reducing fuel consumption.

Synergies with National and Homeland Security (3): This Challenge is applicable to military aircraft.

Support to Space (9): General principles associated with this Challenge apply to high-Mach-number space launch vehicles.

Why NASA?

Supporting Infrastructure (3): NASA has led the development of new turbomachinery computing infrastructure, including the Numerical Propulsion System Simulation tool, now used for many U.S. aircraft engine development and integration efforts. NASA s code framework could be expanded to fully encompass the modeling requirements of integrated systems.

Mission Alignment (9): This Challenge is very relevant to NASA s mission. Novel configurations offer significant potential for breakthroughs in aircraft performance.

Lack of Alternative Sponsors (3): NASA has an important contribution to make to this Challenge. DoD and industry will also support relevant R&T. Collaboration is suggested whenever possible.

Appropriate Level of Risk (9): This Challenge faces high risk.

B8 Propulsion systems for supersonic flight

Commercially viable supersonic propulsion remains an elusive goal. To be successful, a commercial supersonic aircraft must simultaneously meet environmental standards related to local air quality, noise, sonic boom, and high-altitude emissions; performance requirements in terms of T/W, specific fuel consumption, etc.; and FAA certification requirements (NRC, 2001). With the last flight of the Concorde in 2003, the world entered a hiatus from commercial flight at a Mach number greater than 1. At least two American companies are trying to build and fly a supersonic business jet with a capacity of about 12 people by 2012 (<www.aerioncorp.com>; <www.saiqsst.com>). No efforts to build a commercial supersonic transport (with a capacity, for example, of more than 100 people) are under way.

Faster travel is a natural progression of any transportation system. In the case of affordable supersonic flight, shorter travel times, especially on long transoceanic and transcontinental routes, are highly desirable. A profitable supersonic transport would open a new avenue of growth for the U.S. aerospace industry. Two previous NRC studies (NRC, 1997, 2001) specifically focused on commercial supersonic flight, its complexities, and a possible roadmap forward.

Today, federal regulations (14 CFR 91 ¶817) ban civil supersonic flight over the continental United States. Furthermore, since 1994, the FAA has had a supersonic noise policy stating that any future supersonic airplane must have no greater noise impact on a community than a subsonic airplane. After January 1, 2006, that means the aircraft design must also meet Stage 4 noise standards. Defining and achieving acceptable sonic boom levels and reducing community noise to Stage 4 levels, with sufficient margin to account for additional noise restrictions that may be imposed in the future, are critical to making supersonic commercial flight viable. Particularly for supersonic flight, propulsion systems development needs to be integrated with the design of the rest of the aircraft in a multidisciplinary effort to find an optimal trade-off between performance, efficiency, noise, emissions, and thermal management. Engine–airframe integration becomes more critical as the flight speed increases. This Challenge requires validated physics-based numerical simulation codes for component-level analysis and the improvement of multidisciplinary, system-level design tools for vehicle analysis. Technology development should proceed in close coupling with psychoacoustic research to establish acceptable noise levels, especially for sonic booms in inhabited areas, and with climate impact research to establish appropriate emissions levels. As the cruise Mach number increases, a more integrated approach to thermal management is needed to efficiently reject or use the increased amounts of both aerodynamic heat and waste heat generated by the propulsion and power systems. Gas turbine research topics of interest include

- Variable-cycle engines optimized for both subsonic and supersonic flight with low specific fuel consumption, high T/W, and low noise.
- Lightweight, low-noise, efficient inlets and nozzles that also reduce wave drag and help in efficient sonic boom shaping.
- Integrated airframe and propulsion controls to actively reduce vibration mode interactions between the engine and the plane (NIA, 2005).
- Noise and emissions data to validate models for sonic boom signature and its effect on humans (psychoacoustics), to assess the interaction of combustion products with ozone, and to help establish or confirm noise and emissions regulations.
- Electric actuation systems to eliminate the need for high-temperature hydraulic actuation systems.
- Active flow control to improve engine efficiency, reduce noise, and enable different airframe–propulsion integration concepts.
- Combustion process physics: modeling and experimental validation of injection, mixing, ignition, finite-rate kinetics, turbulence–chemistry interactions, and combustion instability to improve efficiency and life.
- Advanced materials and coatings (including high-temperature alloys for compressor and turbine disks) that meet requirements for operating temperature, service life, strength, and propulsion system noise.
- Alternative engine cycles for supersonic flight might replace or enhance traditional gas turbines.

Many of these technologies are included in other R&T Challenges; much of the research proposed for subsonic engines will build a foundation for supersonic flight. In addition, knowledge gained through NASA s High Speed Research Program and DARPA s Quiet Supersonic Platform Program should be leveraged in the search for a new generation of commercial supersonic aircraft.

The technology issues for commercial supersonic transports become more difficult as cruise speed increases. The technology issues for commercial supersonic transports with cruise speeds below approximately Mach 2 are more tractable than those for higher cruise speeds. Key milestones include

- Establish needed boundary conditions, initial conditions, and other inputs and outputs for each module of multidisciplinary, system-level design tools.
- Develop technology that will enable supersonic aircraft to meet Stage 4 noise standards.
- Validate boundary layer control techniques for inlet performance and drag reduction.
- Demonstrate a supersonic variable-cycle engine with specific fuel consumption of 1.1 or lower and a T/W of at least 6 (NIA, 2005).
- Demonstrate high-performance, low-drag, noncircular inlet designs (NIA, 2005).
- Obtain flight test data on noise, emissions, human annoyance caused by sonic boom, and system interactions across the flight regime.

Supersonic aircraft represent the next step toward hypersonic aircraft. Most of the technologies matured for supersonic aircraft can become the starting point for hypersonic aircraft. To cite a few examples, variable-cycle engines proposed for optimized supersonic flight could be a starting point for combined cycles for access to space. Some high-temperature composites or alloys developed for supersonic flight will also carry over to hypersonic flight. Finally, a more-electric engine will likely transition to hypersonic applications.

In summary, the development of propulsion systems for supersonic transports may require NASA or some other federal agency to support the multidisciplinary, multiyear effort described by this Challenge.

Relevance to Strategic Objectives

Capacity (3): Increasing the speed with which people and goods are moved from one place to another directly increases capacity.

Safety and Reliability (1): This Challenge is not relevant to this Objective.

Efficiency and Performance (3): Supersonic flight improves performance but reduces efficiency, because higher speed increases fuel consumption.

Energy and the Environment (1): Supersonic flight has potentially negative environmental impacts, which need to be mitigated for supersonic flight to become viable.

Synergies with National and Homeland Security (9): This Challenge is very relevant to supersonic military aircraft.

Support to Space (9): This Challenge will be applicable to combined cycles, including air-breathing supersonic flight, for access to space. Many of the technologies developed for supersonic flight can also be transitioned to hypersonic flight.

Why NASA?

Supporting Infrastructure (9): NASA has a unique collection of facilities tailored for supersonic flight research, such as the Langley Unitary Plan Wind Tunnel, the Supersonic Low Disturbance Tunnel, and the 20-inch Supersonic Wind Tunnel. NASA also has staff that know how to operate such facilities and have done extensive research in this area (e.g., the High Speed Research program).

Mission Alignment (9): This research is very relevant to NASA s mission to transform our nation s air transportation system and to support future air and space vehicles.

Lack of Alternative Sponsors (3): DoD already supports supersonic R&T for military applications, and industry could sponsor work in this area, especially for development of supersonic business jets.

Appropriate Level of Risk (9): Commercial supersonic flight is a long-range, high-risk Challenge, but it is achievable.

B9 High-reliability, high-performance, and high-power-density aircraft electric power systems

Future aircraft power systems must be able to meet the demands of what is being called the "more-electric aircraft" (MEA). Future aircraft will progressively replace more and more mechanical and hydraulic systems with electrical systems, and electrical loads imposed by conventional systems will also continue to grow, to improve performance, convenience, and reliability. The higher power requirements of conventional loads is being driven by advances in avionics as well as by passenger entertainment and productivity needs. For example, the electric power demand on Boeing s 787 is nearly 1 MW, which is double that of the Boeing 777 and many times that of the first U.S.-built commercial jet, the Boeing 707 (Ames, 2005). The growth of new MEA loads is being driven by advances in the capabilities of electric actuators and controls, and it is being enabled by the development of more flexible and reliable aircraft generators. This Challenge can be met by improving key components and system-level technologies.

Below is a representative list of the potential benefits of future advanced aircraft power systems and a sampling of the technology developments that will enable them.

- *Power efficiency.* Reduction of heat dissipated by the power system to minimize the on-board thermal management problems.
- *Energy efficiency.* Reduction of fuel consumed for electric power generation by up to 20 percent.
- *Power density.* Reduction of power system weight and volume per unit of power generated, processed, and delivered to the load.
- *Energy density*. Fivefold reduction of weight and volume of (1) energy storage components, such as batteries and ultracapacitors, and (2) static electric power plants, such as fuel cells.
- *Flexibility.* Ability to upgrade or evolve the power system as the component technologies or the system mission changes.
- *Reliability.* Ability of the power system to perform without malfunctions and to recover from or adapt to full or partial faults and failures (short circuits, open circuits, control and component failures, aging, and so on).
- *Stability.* Ability of the system to maintain performance integrity in the presence of deleterious dynamics caused by sudden change in the states of the loads or in the power management and distribution (PMAD) system.
- *Advanced system engineering and development methodologies*. Advanced analytical and computer modeling of multiconverter aircraft power systems and controls.
- *Advanced component development.* Wireless control systems, compact, high-efficiency electric motors and generators, advanced sensorless electric machine controls for improved performance, and advanced PMAD systems, including model-referenced control of power systems.
- *High-power-density electric generators*. Integrated engine–generator architectures, such as a high-power-density electric generator on the low-pressure turbine shaft.

Present aircraft power systems are similar to other vehicle power systems, with a generator coupled to the engine through drives and gears. Generators on transport aircraft are generally connected to a 400-Hz power bus, which feeds the loads through manual or electronic switches, with some automatic PMAD functionality. Conventional aircraft power systems will become too large, heavy, inefficient, and inflexible if they are scaled up to supply the power demands of future MEA. Therefore, fundamentally better architectures and technologies for aircraft power systems must be developed to improve the weight and volume density of power systems by factors of 10 and 2, respectively (Emadi et al., 2003). Key milestones include

- Demonstrate tenfold increase in power density for suitable electric generators and motors.
- Demonstrate fivefold increase in energy and power density of suitable batteries and hybrid storage systems (e.g., the battery–ultracapacitor).
- Demonstrate an order of magnitude lighter optimized power system architectures (including, for example, a DC power bus, remotely controlled loads, and a wireless system control).
- Demonstrate intelligent PMAD using advanced system models and wireless sensors or sensorless control technologies for graceful degradation and failsafe operation.
- Demonstrate advanced analysis and simulation tools for multiconverter power systems, which can predict new modes of system dynamics and instability.

Relevance to Strategic Objectives

Capacity (1): This Challenge is not relevant to this Objective.

Safety and Reliability (3): Aircraft safety, to a moderate extent, and aircraft reliability, to a greater extent, will be improved by aircraft power systems with improved stability and fault tolerance.

Efficiency and Performance (9): Aircraft efficiency and performance will be improved by this Challenge due to improved aircraft design, improved PMAD, improved electric power generation, and intelligent system behavior.

Energy and the Environment (3): More efficient electrical systems will reduce fuel burn and emissions.

Synergies with National and Homeland Security (3): This Challenge is relevant to manned and unmanned military aircraft and will improve the performance of reconnaissance and surveillance aircraft for homeland security missions.

Support to Space (3): This Challenge is relevant to space launch vehicles.

Why NASA?

Supporting Infrastructure (1): NASA does not have any significant supporting infrastructure for the development of MEA technologies.

Mission Alignment (9): This Challenge is very relevant to NASA s mission, due to its key role in the advancement of aircraft technology.

Lack of Alternative Sponsors (3): Industry is supporting some R&T related to this Challenge. However, some of the basic knowledge and tools, such as multiconverter power system analysis and simulation models, are unlikely to be developed without NASA s support.

Appropriate Level of Risk (9): This Challenge faces significant risk.

B10 Combined-cycle hypersonic propulsion systems with mode transition

The United States has made significant progress in hypersonic flight technology over the past 40+ years; however, a renewed effort is needed if it is to continue to progress toward making hypersonic flight viable and to maintain world leadership in this challenging and critical technology. This is especially relevant in today s environment, where Japan (Kakuda Space Center) and Germany (DLR) have some of the best high-enthalpy test facilities in the world. Australia (University of Queensland), like the United States, has also flight-tested a hydrogen-fueled scramjet. The two pacing technologies for hypersonic flight are the propulsion system, the topic of this R&T Challenge, and high-temperature materials, which is one of the R&T Thrusts in this Area, propulsion and power.

The primary NASA hypersonics mission is for access to space in support of the space initiative and in placing and maintaining scientific payloads in low Earth orbit. A two-stage-to-orbit (TSTO) vehicle using a hydrogen-fueled, air-breathing first stage and a hydrogen-fueled rocket second stage, could double the payload fraction to low Earth orbit relative to a two-stage hydrogen-fueled rocket (P. Buckley, AFRL, "Payload mass fraction vs. staging velocity for TSTO vehicles to 51.7° orbit," Presentation to the DoD Technology Area Review and Assessment on March 29, 2004). This greatly reduces the cost of putting a payload into orbit. In addition, air-breathing hypersonic vehicles offer the potential for airplanelike operations, with increased safety and efficiency, robust operation, and mission flexibility relative to rockets. A secondary mission for NASA hypersonics is to provide synergy with the DoD programs in the development of missiles for time-critical mobile targets; global strike and rapid resupply aircraft; and routine, on-demand space launch for placing, maintaining, and protecting key satellites in orbit.

NASA s X-43A hypersonic vehicles demonstrated thrust greater than drag at Mach 7 and Mach 10. These were the first in-flight tests of scramjets on a flight vehicle. The X-43A propulsion system was designed to operate at a fixed Mach number (rather than accelerate the vehicle to higher speeds), had enough fuel for just a few seconds of powered flight, and used a heat-sink structure (instead of a fuel-cooled structure, which is needed for a cruise vehicle). Designing a vehicle to accelerate from takeoff to hypersonic speeds, while managing the thermal loads on the aircraft, is still a considerable problem.

One combined-cycle hypersonic propulsion system under study for access to space is a turbine-based combined-cycle (TBCC) system. This system uses a turbine to accelerate the vehicle from takeoff to Mach 3+. At about Mach 3.5, the system transitions to operate as a ramjet and then operates in a dual mode (mixed subsonic and supersonic) from about Mach 4.5 to 5.5. At about Mach 5.5, the system transitions again to operate as a scramjet for TSTO or for single stage to orbit (SSTO). A lot of research has been conducted on steady-state engine operation in the three modes, but transients associated with mode transitions are very difficult to study experimentally or to model numerically. Since all hypersonic vehicles will experience mode transitions on acceleration and deceleration between Mach 3 and Mach 6, it is critical that these transients be well understood.

In order to design complex, combined-cycle hypersonic propulsion systems, experimentally validated, physics-based tools must be developed and refined, because steady, full-enthalpy, clean air conditions cannot be reproduced in hypersonic ground test facilities. Experiments must be conducted on unit problems (e.g., jet injection into a supersonic stream) that contain the relevant flow physics but are amenable to simulation. Facility upgrades, such as for long-duration, high-temperature testing of engine materials and structures, should be completed to conduct the unit experiments under near-realistic flight conditions. Advanced instrumentation must be developed and used to obtain detailed databases in unit problem experiments for complete validation of computational tools that can then be used for the vehicle design. Multiple-point validations are needed to verify that the tools produce results that can be extrapolated to conditions not available on the ground. Ultimately, flight testing must be conducted in order to obtain results under realistic operating conditions. Low-cost flight experiments on suborbital rockets should be exploited in lieu of experiments on expensive flight vehicles.

Figure B-3 delineates some of the fundamental problems that must be addressed during development and validation of computational tools for engine components:

- *Inlet*. Shock wave–boundary layer interactions, prediction of turbulence amplification by shocks (currently overpredicted by Reynolds-averaged Navier-Stokes (RANS) methods), 3-D spillage, starting mechanism, and off-design performance.
- *Isolator*. Prediction of shock train generated by combustion backpressure or engine contraction ratio, and unsteady flow due to cowl door or lip movement.
- *Isolator/combustor*. Dual-mode operation governed by complex interactions of boundary layer separation, shock-boundary layer interaction, shock–shock interactions, fuel-air mixing and combustion efficiency, and chemical kinetics.
- *Combustor*. Modeling of injection, mixing, ignition, and flameholding by LES and other techniques, subgrid scale modeling of turbulent combustion, RANS/LES transition methodology, excessive dissipation in LES modeling of mixing and combustion, probability density function transport modeling of species mixing, turbulence–chemistry interactions, and finite-rate chemistry.
- *Nozzle*. Thermal and chemical nonequilibrium, and boundary layer relaminarization.

Once these component-level models have been developed and validated, they can be integrated to create a full vehicle, tip-to-tail computational tool.

Milestones should mark the completion of validated component-level models using appropriate facilities, unit experiments, and advanced diagnostics. Key milestones include

- Develop advanced diagnostics capable of measuring time-averaged and time-resolved flow parameters and their correlations.
- Demonstrate ramjet-scramjet (dual-mode) transition and isolator performance for a simplified geometry with alternately clean and vitiated air.
- Conduct transient experiments to simulate cowl door movement for turbine-ramjet mode transition and cowl lip movement to control inlet contraction.
- Demonstrate injection, mixing, and combustion using simple fuel injectors and with alternately clean and vitiated air.
- Conduct inlet studies with variable angles of attack and sideslip angles.
- Investigate new engine configurations using inward-turning inlets, elliptical cross-sections, etc.

Relevance to Strategic Objectives

Capacity (1): This Challenge has no impact on this Objective.

Safety and Reliability (1): This Challenge has no impact on this Objective.

Efficiency and Performance (3): This Challenge will improve the understanding of complex fluid and structural physics at hypersonic speeds, which will be useful for understanding lower speeds as well.

Energy and the Environment (1): This Challenge has no impact on this Objective.

Synergies with National and Homeland Security (9): Hypersonic propulsion systems being developed by the DoD will benefit significantly from a NASA research program in combined-cycle propulsion systems with mode transition.

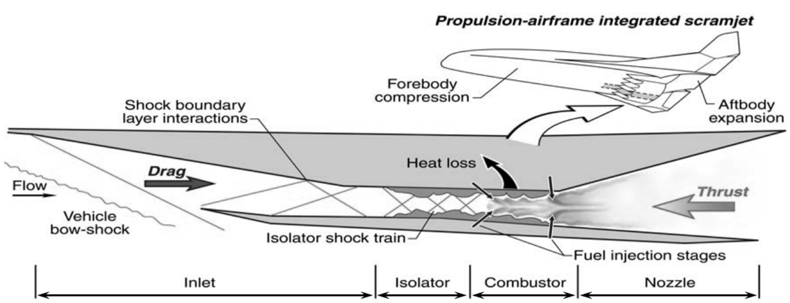

FIGURE B-3 Technology issues in supersonic combustion ramjets. SOURCE: NASA, 2006.

Support to Space (9): This Challenge is very relevant to NASA s space exploration and access-to-space missions.

Why NASA?

Supporting Infrastructure (9): NASA has relevant facilities (e.g., Langley s 8-Foot High-Temperature Tunnel, Arc-Heated Scramjet Test Facility, Combustion-Heated Scramjet Test Facility, Direct Connect Supersonic Combustion Test Facility, 15-Inch Mach 6 High-Temperature Tunnel, 20-Inch Mach 6 CF4 Tunnel, 20-Inch Mach 6 Tunnel, 31-Inch Mach 10 Tunnel) and expertise that are uniquely capable of supporting the development of combined-cycle hypersonic propulsion systems.

Mission Alignment (9): This Challenge is very relevant to several items in NASA s charter.

Lack of Alternative Sponsors (3): Both NASA and the DoD support the development of hypersonic propulsion systems.

Appropriate Level of Risk (9): This Challenge faces high risk, too much for industry to take the lead, but it has a good chance of success if the program is supported adequately over the next decade.

B11 Alternative fuels and additives for propulsion that could broaden fuel sources and/or lessen environmental impact

Current aircraft are designed to operate on kerosene, which, like other transportation fuels in the United States, is currently derived from petroleum. The U.S. transportation sector increases U.S. dependence on foreign oil. The environmental impact of current fuels, which emit, among other things, NO_x, SO_x, particulates, and greenhouse gases (CO_2 and H_2O), is coming under increasing scrutiny. These issues, coupled with the long-term inability of gains in energy efficiency to fully offset increasing demand, provide impetus for alternative fuels for transportation in general and aviation in particular. Alternative fuels for transportation include liquid fuel derived from domestic shale oil and coal (e.g., kerosene produced from gasified coal via Fisher-Tropsch chemistry), biomass-derived fuels, natural gas, hydrogen, methanol, and ethanol. That last two have significantly lower energy densities (heating values of 22.6 and 29.7 MJ/kg, respectively, relative to about 43 MJ/kg for gasoline) and are therefore less likely candidates for aviation fuel. The energy density of hydrogen by weight is high (120 MJ/kg), but the energy densities by volume of hydrogen and natural gas are very low compared to liquid fuels, which creates storage problems that are difficult to solve when it comes to aviation. Key performance metrics for any alternative fuel include cost, availability, sustainability, energy density, pollutant emissions, greenhouse gas emissions, and safety.

Use of alternative fuels such as synthetic kerosene, methane, or hydrogen could reduce aircraft emissions and mitigate U.S. dependence on imported crude oil, thereby increasing sustainability. For example, hydrogen would enable engines with zero emissions of CO, SO_x, particulates, and CO_2, but large emissions of water vapor, which could exacerbate environmental issues associated with contrails (NRC, 2002). Synthetic kerosene derived from domestic resources could be cleaner and emit lesser amounts of particulates and SO_x. The environmental benefits of an alternative fuel would, of course, need to be quantified. Alternative aviation fuels would provide significantly less benefit than alternative fuels for ground-based transportation, because aviation accounts for only 2.6 percent of U.S. greenhouse gas emissions compared to the 28 percent share accounted for by the total transportation sector (EPA, 2006).

DOE, DoD, and industry support most alternative fuels research. Within DOE, significant efforts have been under way to develop alternative fuels for the automotive sector, including compressed natural gas, methanol, ethanol, biomass-derived fuels, hydrogen (the hydrogen fuel initiative was reviewed in a recent NRC report (NRC/NAE, 2004)). The U.S. Air Force conducted extensive research in the late 1970s and early 1980s to develop alternative aviation fuels from shale oil, coal, and tar sands, and tested them extensively in military engines. The DoD also has a new initiative in clean fuels (Barna et al., 2005).

The key technical questions associated with alternative fuels for civilian aviation are cost, availability, the ground transportation and storage infrastructure, onboard storage, combustion, quantification of environmental impacts, and certification. All of the potential alternative fuels are currently more expensive than conventional jet fuel (Saynor et al., 2003), so large-scale, cost-effective production of alternative fuels (particularly synthetic kerosene and hydrogen) still requires significant research. Recent reports address in detail the technical barriers for hydrogen production (NRC/NAE, 2004; DOE, 2003).

No commercial aircraft or engines have been designed to operate using alternative fuels, so airframe and auxiliary systems as well as new engines and fuel injection systems for handling these fuels remain to be developed. Onboard storage systems for natural gas and hydrogen would require significant modifications to existing aircraft or new airframe designs (NRC, 2002). Hydrogen-based fueling concepts have been advanced and investigated since the 1950s (Saynor et al., 2003; Faass, 2001). Aircraft combustors capable of handling gaseous fuels such as methane and hydrogen or prevaporized liquid fuels will need to address a variety of dynamic combustor operability phenomena, such as blow-off, flashback, and combustion instabilities—problems that are still poorly understood in ground-based turbines that already use gaseous fuels. Fundamental combustion research, with particular focus on pollutant formation and unsteady combustor phenomenon, would be required to address these issues. Fuel specifications would also need to be defined to assure quality and consistency worldwide.

Research is needed to quantify the costs and environmental benefits of alternative fuels. For example, production and delivery of hydrogen as currently practiced could increase overall greenhouse gas emissions (NRC/NAE, 2004). Alternative fuel development for civilian aviation will, with reason, lag that for ground-based transportation due to the significantly greater problems associated with aviation applications and the larger research efforts necessary to solve them. NASA should monitor the progress of the DOE and DoD programs and take advantage of synergies, as appropriate. Key milestones include

- Develop mechanisms to monitor and interact with ongoing efforts in DOE, DoD, and elsewhere to develop alternative fuels with possible application to civil aviation.
- Develop specifications for alternative civil aviation fuels.
- Develop understanding of and predictive capabilities for correlating the molecular composition of fuels with their bulk properties (e.g., density, lubricity, stability, and emissions).
- Understand the various means, including additives, of enhancing the performance (e.g., lubricity, stability, emissions, performance) of alternative fuels.
- Understand chemical mechanisms and develop validated models that describe combustion for alternative fuels.
- Develop advanced testing methods and standards for alternative fuels.

Relevance to Strategic Objectives

Capacity (3): A long-term supply of sustainable fuels with reduced emissions would help eliminate constraints on growth in capacity.

Safety and Reliability (1): This Challenge has little or no relevance to this objective.

Efficiency and Performance (3): Development of alternative fuels is motivated primarily by emissions and sustainability concerns. However, alternative fuels would also affect the efficiency and performance of aircraft engines and, indirectly, the air transportation system as a whole.

Energy and the Environment (9): The long-term impact of alternative fuels with reduced emissions could greatly reduce the environmental effects of aviation.

Synergy to National and Homeland Security (3): Alternative fuels developed for civil aviation could probably also be used by military aircraft, and this Challenge would support ongoing work by the DoD on alternative fuels.

Support to Space (1): This Challenge has little relevance to this Objective because the amount of fuel used to support the space program is quite small compared to that for ground and air transportation.

Why NASA?

Supporting Infrastructure (3): NASA has the technical expertise to address engine combustor issues and, in collaboration with industry, aircraft design issues associated with alternative fuels.

Mission Alignment (3): Some aspects of this Challenge, such as the investigation of combustion issues, are very relevant to NASA s mission, but other aspects, such as fuel production and delivery, are not.

Lack of Alternative Sponsors (3): DOE, DoD, and industry are supporting research relevant to this Challenge, although NASA support is necessary to address all issues concerning the use of alternative fuels for civil aviation.

Appropriate Level of Risk (9): Use of alternative fuels is a long-term problem that faces moderate risk.

B12 Hypersonic hydrocarbon-fueled scramjet

DoD has had operational hypersonic systems for the past 40+ years in the form of intercontinental ballistic missiles, launch vehicles, and reentry vehicles. The Air Force s *Vision 2020: Global Vigilance, Reach and Power* (USAF, 2000) stated that the service should strive for "controlling and exploiting the full aerospace continuum." NASA programs to develop hypersonic propulsion systems should be coordinated with similar DoD efforts.

In the near term, hydrocarbon-fueled scramjets can be used to power rapid response aircraft, missiles, and expendable space lift vehicles. In the medium term, combined-cycle engines can propel rapid global response and reconnaissance aircraft. These engines, such as the TBCC, operate in several engine modes (see R&T Challenge B10). In the far term, combined-cycle engines can be used for access-to-space vehicles.

Air-breathing hypersonic propulsion systems for space access could enable aircraftlike operations, increasing mission flexibility and payload fraction relative to rocket-based propulsion systems. For NASA and DoD access to space, a TSTO vehicle could use a hydrocarbon fuel in the first stage and a hydrogen fuel for the second stage. The fuel of choice for most DoD applications will be hydrocarbons because of their high energy density, good heat capacity, and storability.

Significant ground testing has been done by the DoD on hydrocarbon-fueled scramjets. In addition, the Air Force scramjet-engine-demonstrator is being developed to demonstrate scramjet operation in flight, with a scramjet takeover at Mach 5.5 and cruise at Mach 6.5 to 7.0. NASA has already demonstrated in-flight operation of a scramjet at Mach 7 and Mach 10 in the X-43A program.

The development of hydrocarbon-fueled hypersonic propulsion systems will require many of the same basic technologies as those that are hydrogen-fueled. See B10 for a detailed listing of the issues involved. Key milestones include

- Develop advanced instrumentation capable of measuring time-averaged and time-resolved flow parameters to validate design tools.
- Complete unit experiments based on generic inlets, isolators, combustors, and nozzles to provide benchmark data sets for model validation.
- Conduct experiments on mode transition for validation of unsteady models.
- Assist DoD flight demonstration programs that are currently in progress.

Relevance to Strategic Objectives

Capacity (1): This Challenge has no impact on this Objective.

Safety and Reliability (1): This Challenge has no impact on this Objective.

Efficiency and Performance (3): This Challenge will improve the understanding of complex fluid and structural physics at hypersonic speeds, which will be useful for understanding lower speeds as well.

Energy and the Environment (1): Environmental impact is likely to be small given the small number of hypersonic vehicles likely to be produced.

Synergies with National and Homeland Security (9): Hypersonic propulsion systems being developed by the DoD will benefit significantly from this Challenge.

Support to Space (9): This Challenge is very relevant to NASA and DoD development programs for access-to-space vehicles.

Why NASA?

Supporting Infrastructure (9): NASA has relevant facilities (e.g., Langley s 8-Foot High-Temperature Tunnel, Arc-Heated Scramjet Test Facility, Combustion-Heated Scramjet Test Facility, Direct Connect Supersonic Combustion Test Facility, 15-Inch Mach 6 High-Temperature Tunnel, 20-Inch Mach 6 CF4 Tunnel, 20-Inch Mach 6 Tunnel, 31-Inch Mach 10 Tunnel) and expertise that are uniquely capable of supporting the development of DoD hypersonic propulsion systems.

Mission Alignment (3): This R&T Challenge has some relevance to the NASA mission, but would mainly be in support of DoD research.

Lack of Alternative Sponsors (3): Both NASA and the DoD support the development of hypersonic propulsion systems.

Appropriate Level of Risk (9): This Challenge faces high risk, too high for industry to take the lead, but it has a good chance of success if the program is supported adequately over the next decade.

B13 Improved propulsion system tolerance to weather, inlet distortion, wake ingestion, bird strike, and foreign object damage

Over the last 20 years, considerable progress has been made in engine and propulsion system design to address issues related to tolerance to weather, inlet distortion, wake ingestion, bird strike, and foreign object damage (FOD). Requirements are becoming more and more stringent, however, and more work remains to be done. This is particularly the situation with the advent of larger inlets on commercial engines, which makes engines more susceptible to bird ingestion and FOD.

To accommodate adverse weather (e.g., rain, ice, hail, and crosswinds), better analytical models are needed to predict the impact of the elements on fans, compressors, and combustor stability. These models should be physics-based and validated with experimental data. Detailed weather data as a function of altitude are needed for altitudes up to 20,000 ft; data on water concentration and droplet size are especially important. Analyses of the impact of ingested rain, ice, and so on as they traverse the propulsion system need to be improved. Better models will lead to more robust engine designs and improved operational procedures.

Better designs are also needed to toughen turbomachinery against bird ingestion and FOD without a significant loss in performance. This will require better materials and better design techniques. Development of improved aircraft and engine controls should also be considered to maximize the ability of aircraft to withstand to these events. Key milestones include

- Improve analytical tools to model more accurately the effects of rain, ice, and hail ingestion on engine behavior.
- Improve fan, compressor, and combustor stability to anomalous events.
- Collect detailed data about weather at altitude, particularly water concentration and droplet size, up to 20,000 ft.
- Improve impact resistance of turbomachinery.
- Improve engine and aircraft controls to adjust for impact events and erosion.

Relevance to Strategic Objectives

Capacity (3): Reduced sensitivity to weather and operational anomalies would increase capacity during adverse weather.

Safety and Reliability (9): This Challenge will increase safety and reliability by reducing the probability and severity of malfunction when the engine encounters anomalies.

Efficiency and Performance (3): This Challenge will minimize performance degradation through increased robustness.

Energy and the Environment (1): Improved robustness should maintain current levels of noise and emissions.

Synergies with National and Homeland Security (3): This Challenge will also benefit DoD aircraft.

Support to Space (1): This Challenge has very little relevance to this objective because space launch and return-to-Earth can generally avoid poor weather by altering schedules.

Why NASA?

Supporting Infrastructure (3): NASA has a few relevant facilities, such as icing tunnels.

Mission Alignment (3): This Challenge is relevant to NASA s mission of improving the safety and capacity of the air transportation system.

Lack of Alternative Sponsors (3): Industry and DoD are much more active than NASA in supporting research relevant to this Challenge. It has enough payoff and impact for industry to pursue.

Appropriate Level of Risk (3): This Challenge faces low risk.

B14 Propulsion approaches employing specific planetary atmospheres in thrust-producing chemical reactions

The three types of power sources for producing vehicle thrust in planetary atmospheres are electric, chemical, and nuclear. Electrical sources include solar cells, fuel cells, and batteries. Chemical sources involve combustion of a fuel in the presence of an oxidizer (bipropellant) or a catalyst (monopropellant) in an internal combustion engine, a piston expander, a gas turbine, or a rocket. Only chemical propulsion can produce the thrust levels needed for practical flight in planetary atmospheres.

The inner terrestrial planets—Mercury, Venus, Earth, and Mars—are too small to have prevented the light gases, hydrogen and helium, from being blown away by the solar wind; in fact, Mercury has only a trace atmosphere. Venus and Mars have about 96 percent CO_2 atmospheres, with Venus s atmosphere being very acidic. Titan s atmosphere is about 95 percent nitrogen but contains many hydrocarbons. The outer (Jovian) planets, Jupiter, Saturn, Uranus, and Nepture, are large enough to have retained gases from a nearby nebula; therefore, their atmospheres are all about 80-97 percent hydrogen, with several percent helium and methane. Mars and Venus, therefore, have oxidizing atmospheres, whereas Titan and the Jovian planets contain hydrogen or hydrocarbon, which can be used as fuels in a planetary flight vehicle. The method of propulsion from chemical reaction is, therefore, quite different for each planet.

Propulsion systems for planetary flight vehicles on Mars have received a lot of study and increasingly so with NASA s Space Exploration Initiative. Combustion of metals in CO_2 is the most promising source of energy for these vehicles. Using the CO_2 in the atmosphere of Mars averts the need to transport an oxidizer, greatly simplifying the spacecraft system and increasing its payload fraction. Magnesium is currently recognized as the best candidate fuel owing to its high adiabatic flame temperature, high specific impulse at high oxidizer:fuel ratios, high heat per unit mass, and low ignition temperature. The effective specific impulse of magnesium combustion in carbon dioxide is 1,190 seconds for an oxidizer:fuel ratio of 6. Magnesium also combusts at pressures suitable for internal combustion or turbine engines on Mars. It can be liquefied for use in a bipropellant rocket motor. It may be possible that, in the future, magnesium will be produced directly on Mars since the Viking Landers found that martian soil is 5 percent magnesium. The combustion of magnesium in CO_2 could become the main source of energy for human exploration on Mars.

Fundamental studies have been conducted on the burning of magnesium particles in CO_2. Simplified particle combustion models include two reactions zones: an outer zone, where magnesium reacts at a transport-limited rate to form condensed magnesium oxide plus carbon monoxide, and an inner zone, at the particle surface, where carbon monoxide reacts with liquid magnesium to form solid carbon and solid magnesium oxide, which remain with the particle. Kinetic mechanisms have been investigated and burning rates calculated and measured.

Considerable research needs to be done on engine cycles that operate with small magnesium and magnesium oxide particles. A gas turbine would have to operate with these erosive particles and would need a large inlet and exhaust nozzle owing to the rarefied atmosphere on Mars (about 1 percent of that on Earth). Internal combustion engines would have to be supercharged owing to the rarefied atmosphere. Binders for the magnesium and methods for supplying the gaseous or liquefied carbon dioxide to a rocket is another topic for research. Key milestones include

- Conduct detailed investigations, numerical and experimental, of the fundamental combustion characteristics of fuels or oxidizers that could be used in conjunction with the specific materials that make up the planetary atmospheres.
- Perform research on engine cycles that can operate with the indigenous atmospheric materials.
- Demonstrate propulsion systems found to be most promising for planetary flight vehicles in atmospheres of interest.

Relevance to Strategic Objectives

Capacity (1): This Challenge has no impact on this Objective.

Safety and Reliability (1): This Challenge has no impact on this Objective.

Efficiency and Performance (1): This Challenge has no impact on this Objective.

Energy and the Environment (1): This Challenge is not relevant to this objective.

Synergies with National and Homeland Security (1): This Challenge is not relevant to this Objective.

Support to Space (9): This Challenge provides a significant contribution to NASA s space exploration initiative to Mars and beyond.

Why NASA?

Supporting Infrastructure (3): NASA has relevant facilities and expertise, but they are not unique as there are also many ongoing university programs.

Mission Alignment (9): This Challenge area has major relevance and impact on several items in NASA s charter for space exploration as well as aeronautics.

Lack of Alternative Sponsors (9): This is a challenge where NASA would have to take the lead.

Appropriate Level of Risk (9): This Challenge faces high risk.

B15 Environmentally benign propulsion systems, structural components, and chemicals

This R&T Challenge is often referred to as the "green" (sometimes "evergreen") engine. The aim is to minimize the environment impact of gas turbine engines from cradle to grave (i.e., spanning the complete spectrum from manufacturing processes to operations to product end of life and disposal). The green concept generally includes minimizing noise and emissions, but these have already been identified separately as high-priority R&T Challenges and are not explicitly included here. The aim of this Challenge is to use, to the greatest degree possible, structural and maintenance materials that are environmentally benign and that can be recycled or safely disposed of at the end of life; environment-friendly manufacturing methods (e.g., the use of aqueous solvents, cutting fluids, and degreasers); and engine lubricants and working fluids that are environmentally safe. In some cases, human factors issues, such as ergonomically sound manufacturing and maintenance procedures, are included in comprehensive green engine programs.

It is difficult to quantify the environmental benefits of green engineering approaches, but their economic benefits may be easier to quantify. These accrue from less waste and disposal, more recycling of rare or precious materials, and a healthier and safer environment for manufacturing and maintenance personnel.

Significant progress has been made in the last decade in both engine materials and manufacturing processes. New materials include lead-free antigallants; lead-free, nonsilver dry film lubricants; chrome-free coatings; alternatives to cadmium plating and chromium anodizing; and nonchromate primers and coatings. In the manufacturing arena, solvents with low volatile organic content; closed-loop alkalai cleaning; and closed-loop acid pickling, milling, and stripping have been introduced. Key milestones include

- Assess current manufacturing processes and engine bills of materials to identify elements or compounds whose elimination would be environmentally beneficial.
- Quantify environmental benefits likely with elimination of targeted compounds.
- Assess feasibility and estimate the cost-benefit ratio of eliminating targeted compounds.
- Replace targeted compounds with validated substitutes.

Relevance to Strategic Objectives

Capacity (1): Although there may be some economic benefit to the environmental stewardship envisioned in this Challenge, it is unlikely to be sufficiently large to impact the cost of air travel in any significant way.

Safety and Reliability (1): This Challenge is not relevant to the safety of aircraft, although the safety of ground support personnel may be increased slightly (e.g., through the simplification of some maintenance procedures).

Efficiency and Performance (1): This Challenge is not relevant to this Objective.

Energy and the Environment (9): Modest energy savings in manufacturing may accrue from the recycling of precious or rare materials. This Challenge will produce major environmental benefits by reducing the use and disposal of environmentally harmful materials during every phase of product life, from design to end-of-life disposal.

Synergies with National and Homeland Security (3): The adverse environmental impact of DoD gas turbine engine design, manufacturing, maintenance, and disposal would be reduced.

Support to Space (1): This Challenge is likely to have very little relevance to this Objective because of the small number of access-to-space vehicles and the low volume of operations.

Why NASA?

Supporting Infrastructure (3): NASA has a strong materials capability that may be able to contribute to eliminating certain hazardous elements from gas turbine materials. It does not, however, have a comparably strong manufacturing support capability.

Mission Alignment (3): This Challenge is relevant to NASA s mission.

Lack of Alternative Sponsors (3): The Environmental Protection Agency, the Occupational Safety and Health Administration, and industry are likely to continue supporting environmental stewardship issues. Industry, in particular, is motivated by potential economic benefits. However, aeronautics may not be a priority for these groups.

Appropriate Level of Risk (3): This Challenge faces very high risk. In the structural materials area, some chemical constituents are very likely to be absolutely necessary for high performance and cannot be eliminated, so the return on investment may be problematic.

B16 Reduced engine manufacturing and maintenance costs

This Challenge will develop the ability to design engines with simpler, fewer parts that are easily serviceable while maintaining good performance and efficiency. To reduce manufacturing costs, better simulation and modeling tools will be developed to permit the design of engines with higher aerodynamic loadings in compressors and turbines. This will lead to fewer turbomachinery stages and fewer airfoils within each stage. Better materials, less expensive materials, and materials with less variability in properties will reduce the amount of expensive materials that must be used. Better machining and manufacturing techniques will reduce machining time and costs and reduce the amount of scrap, which can be expensive, particularly when exotic materials are involved. Maintenance costs will generally be lowered if engines contain fewer parts (e.g., fewer turbine blades that need to be replaced periodically). In addition, better predictions of the on-wing life of the parts will permit them to be used longer and more efficiently without an increase in malfunctions. More intelligent systems, described in R&T Challenge B3, will permit maintenance personnel to better assess the exposure of engine parts and, therefore, to better predict life. In addition, improved health diagnostics systems will permit maintenance staff to troubleshoot problems quickly and accurately, which will reduce overhaul and repair time. This produces a dual benefit: reducing the costs of overhauls and minimizing engine downtime. Key milestones include

- Improve turbomachinery design tools for reduced stage and part count.
- Develop better materials with narrower tolerances to reduce unnecessarily large design margins.
- Develop low-cost materials with the same high-performance properties.
- Develop better manufacturing techniques to reduce scrap.
- Develop better on-wing life predictions to minimize premature retirement of parts.
- Develop improved health diagnostics to allow performing maintenance as required rather than as scheduled (predictive maintenance).
- Develop intelligent engines that can adjust operation to minimize degradation of parts.

Relevance to Strategic Objectives

Capacity (3): Lower acquisition and maintenance costs will affect affordability of operations and should allow for profitable increases in capacity.

Safety and Reliability (3): Simpler designs are easier to maintain and are more reliable.

Efficiency and Performance (3): Improved, predictive maintenance should minimize performance degradation.

Energy and the Environment (3): Improved, predictive maintenance should minimize performance degradation and maintain engines near design noise and emissions levels.

Synergies with National and Homeland Security (3): DoD faces similar issues and would benefit from research on civil aircraft.

Support to Space (1): Some materials and techniques, particularly improved health diagnostics, might find applications on space vehicles, but because of differences in materials and flight regimes, benefits would be indirect.

Why NASA?

Supporting Infrastructure (3): NASA has strength in the development of the analytical tools, materials, sensors, and controls.

Mission Alignment (1): Achieving simpler, high-performance designs is very relevant to NASA s mission, but manufacturing technologies are not particularly relevant.

Lack of Alternative Sponsors (1): Industry and DoD are already key players in such initiatives.

Appropriate Level of Risk (3): The risk of this work can range from somewhat incremental to very challenging.

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C

R&T Challenges for Materials and Structures

A total of 20 R&T Challenges were prioritized in the materials and structures Area. Table C-1 shows the results. The R&T Challenges are listed in order of NASA priority. National priority scores are also shown.[1] This appendix contains a description of each R&T Challenge, including milestones and an item-by-item justification for each score that appears in Table C-1.[2]

C1 Integrated vehicle health management

Integrated vehicle health management (IVHM) refers to the ability to monitor, assess, and predict the structural and material health[3] of primary and secondary structures for individual missions and lifetime durability using networks of onboard sensors. A fully integrated approach to IVHM relies on a multidisciplinary set of analysis, testing, and inspection tools, including miniaturized sensors and distributed electronics; sophisticated signal processing; data acquisition, integration, and database maintenance; artificial intelligence; damage science; and the mechanics of structures and their failure.

In addition to the obvious benefit of increasing safety and reliability, IVHM holds the promise of reducing vehicle cost, weight, and maintenance downtime, as well as speeding the introduction of new material systems and structural concepts. Real-time onboard sensor systems that monitor the actual state of materials and structural components enable more efficient use of material, including novel concepts. Moreover, with a national fleet of aging aircraft and infrastructure in an industry with low profit margin, IVHM is increasingly important due to its ability to increase safety and reliability. IVHM promises low-cost, real-time sensing and inspection methods to detect damage before catastrophic failure occurs.

IVHM currently means putting a variety of sensor systems onboard an aircraft, along with the artificial intelligence that automatically interprets the various sensor output streams. These data are used to provide input to prognostic systems that then draw conclusions about structural integrity issues. Two main features distinguish the next generation of IVHM from traditional nondestructive evaluation (NDE): (1) Sensor packages will be very small and exceedingly lightweight and (2) the reliance on humans to interpret the sensor output and assess the impact on structural integrity will be reduced or eliminated. Sensors and software are available, e.g., fiber-optic (Wood et al., 2000; Stewart et al., 2003; Carman and Sendeckyi, 1995) and piezoelectric (Lin and Chang, 2002; Giurgiutiu and Zagrai, 2002). The next major hurdle is integrating IVHM systems in flight structures. Laboratory tests have demonstrated that several classes of IVHM systems are available. Downselects to designs appropriate for aircraft structures are needed.

Three classes of IVHM systems warrant attention over the next 10 years. The first class includes fiber-optic sensor systems that can use multiplexed fibers attached to or embedded in the structure, each with numerous multiphysics sensing sites interrogated in turn by a single electro-optic module. The second class includes locally self-powered, wireless microelectromechanical sensors of various types tiny enough that very large numbers of sensors become practical. Each sensor mote performs a point measurement, so many are used to effectively cover large areas. The third class includes discrete active or passive remotely powered sensor modules (e.g., by means of guided-wave ultrasonic or acoustic emission) that may be large compared to sensor motes but can interpret multimode vibrations or multiphysics parameters (temperature, stress, humidity, etc.) that propagate over relatively long distances within the key structural

[1]The prioritization process is described in Chapter 2.

[2]The technical descriptions for the first 10 Challenges listed below contain substantially more detail than the technical descriptions for these Challenges as they appear in Chapter 3.

[3]"Health" in this context implies either an absence of measurable material flaws or an ability to coordinate the growth rate of flaws with the safe life remaining for the element in question.

TABLE C-1 Prioritization of R&T Challenges for Area C: Materials and Structures

		Strategic Objective							Why NASA?					
		Capacity	Safety and Reliability	Efficiency and Performance	Energy and the Environment	Synergies with Security	Support to Space	National Priority	Supporting Infrastructure	Mission Alignment	Lack of Alternative Sponsors	Appropriate Level of Risk	Why NASA Composite Score	NASA Priority Score
R&T Challenge	**Weight**	**5**		**3**		**1**			**1/4 each**					
C1	Integrated vehicle health management	9	9	3	1	9	3	**114**	9	9	1	9	**7.0**	**798**
C2	Adaptive materials and morphing structures	9	3	9	3	9	3	**108**	9	9	1	9	**7.0**	**756**
C3	Multidisciplinary analysis, design, and optimization	9	3	9	1	3	3	**96**	9	9	3	9	**7.5**	**720**
C4	Next-generation polymers and composites	9	3	9	1	9	3	**102**	9	9	1	9	**7.0**	**714**
C5	Noise prediction and suppression	9	1	3	9	3	1	**90**	9	9	3	9	**7.5**	**677**
C6a	Innovative high-temperature metals and environmental coatings	3	9	3	1	9	3	**84**	9	9	3	9	**7.5**	**630**
C6b	Innovative load suppression, and vibration and aeromechanical stability control	3	9	3	1	9	3	**84**	9	9	3	9	**7.5**	**630**
C8	Structural innovations for high-speed rotorcraft	9	1	3	1	9	1	**72**	9	9	3	9	**7.5**	**540**
C9	High-temperature ceramics and coatings	3	1	9	3	3	9	**68**	9	9	3	9	**7.5**	**510**
C10	Multifunctional materials	3	3	9	3	9	9	**84**	3	9	3	9	**6.0**	**504**
C11	Novel coatings	3	9	3	3	1	1	**80**	3	9	3	9	**6.0**	**480**
C12	Innovations in structural joining	3	3	9	1	3	3	**66**	3	9	3	9	**6.0**	**396**
C13	Advanced airframe alloys	9	1	9	1	3	1	**84**	1	3	1	9	**3.5**	**294**
C14	Next-generation nondestructive evaluation	3	9	1	1	3	1	**70**	3	9	1	3	**4.0**	**280**
C15	Aircraft hardening	1	9	1	1	9	1	**66**	3	3	1	9	**4.0**	**264**
C16	Multiphysics and multiscale modeling and simulation	3	3	3	3	3	1	**52**	3	3	3	3	**3.0**	**156**
C17	Ultralight structures	3	1	3	1	3	3	**38**	3	9	1	3	**4.0**	**152**
C18	Advanced functional polymers	1	3	1	1	3	1	**30**	9	3	3	3	**4.5**	**135**
C19	Advanced engine nacelle structures	3	1	3	1	1	1	**34**	1	9	1	3	**3.5**	**119**
C20	Repairability of structures	3	3	3	1	1	1	**44**	3	3	1	3	**2.5**	**110**

elements. Over the near term, IVHM sensors are more likely to be discrete items integrated with the structure rather than just another function of the structural materials themselves. Over the next decade, however, there is much work to be done in making things small enough, smart enough, and with enough multifunctionality to be acceptable to the airframe designers and owners.

Successful application of IVHM also relies on continued research and refinement in fundamental structural mechanics and the mechanics of damage and failure for accurate interpretation of IVHM sensor data and to support autonomous decision making for damage recovery and mitigation.[4]

NASA's research program should target key applications where IVHM is most likely to make a difference rather than develop monitoring systems for unforeseen problems in existing structures. Detecting and characterizing multidamage states, composite debonding, corrosion, long-term fatigue, and impact damage are all important areas that can be mitigated with IVHM. Assessing the integrity of structural repair patches and finding latent faults in aging wiring are also key issues that need to be addressed over the next decade. IVHM approaches for aging aircraft are typically in response to a problem that has been identified. Regardless of the particular problem, however, the goals are still the same: putting a variety of sensor systems onboard aircraft along with the artificial intelligence that automatically interprets the various sensor output streams to provide input to prognostic systems that then assess structural integrity and makes life predictions. Key milestones include

- Develop lightweight sensor networks that characterize the state of materials and structures over large areas.
- Develop very-low-power or self-powered wireless sensors capable of operation in harsh environments.
- Develop artificial intelligence to automatically assess structural integrity from sensor responses and implement damage mitigation protocols.
- Develop components and sensors that are cost competitive and available from multiple vendors.
- Flight test full-scale IVHM systems to detect multisite damage.

Relevance to Strategic Objectives

Capacity (9): IVHM increases operating flexibility by permitting a wider range of operating conditions and environments due to increased confidence in the actual state of the structural elements. Monitoring system performance in real time allows one to do new things with confidence, such as enabling larger aircraft sizes and new aircraft concepts (for example, V/STOL aircraft, variable-cycle engines, and new structural configurations). These new designs may operate in currently unexplored regimes of operation and greatly increase the flexibility of the air transportation system. In addition, health monitoring could reduce maintenance time and costs. Aircraft could report the predicted lifetimes of their own parts and report the need for replacement parts. IVHM could quickly diagnose root problems, minimizing flight delays (Powrie and Fisher, 1999; Simon, 2000).

Safety and Reliability (9): Early detection of impending failures in aircraft materials, structures, and wiring is critical for avoiding fatalities as a part of the aging aircraft program. IVHM also reduces time lost to scheduled maintenance and reduces the likelihood of unscheduled downtime.

Efficiency and Performance (3): Once confidence in IVHM systems has been established, they could allow aircraft to operate closer to performance margins and with greater structural efficiency, which would reduce operating costs. IVHM will change future aircraft designs by reducing the margin of safety required in design, thereby reducing weight and increasing performance. It will also allow better design of engine fan blades, which now must be overdesigned for fear of fatigue failure. Finally, IVHM could increase the efficiency of aircraft maintenance, reducing operating costs and downtime.

Energy and the Environment (1): This Challenge will increase structural efficiency, which could save energy and thus reduce environmental effects, but overall, the impact is indirect.

Synergies with National and Homeland Security (9): DoD and others are already supporting research relevant to this Challenge but NASA has an opportunity to contribute when it comes to civil aeronautics and with a focus on the more sophisticated sorts of sensor systems that require a high-level understanding of the measurement physics involved. Reducing downtime has a significant impact on mission availability. Because IVHM systems for civil aviation will have to comply with stringent national and international certification requirements, advances will likely appear first in military aircraft.

Support to Space (3): IVHM could allow spacecraft to operate safely closer to performance margins and to be confidently designed with greater structural efficiency. However, differences in operating conditions mean that aeronautical IVHM systems would only be partially applicable to space vehicles.

Why NASA?

Supporting Infrastructure (9): NASA has many experts in technical fields related to IVHM. Facilities of particular relevance include the fiber-optic draw tower at Langley's Nondestructive Evaluation Sciences Branch and the NASA Dryden flight research facility, which provides a platform to test various IVHM approaches in flight.

Mission Alignment (9): IVHM is a natural part of NASA's aeronautics mission and also dovetails nicely with

[4]See R&T Challenges D4 and D5.

NASA's multifunctional materials and multiphysics analysis research, although over the near term IVHM sensors are more likely to be discrete items integrated with the structure rather than just another function of the structural materials themselves. Over the next decade, there is much work to be done in making things small enough, smart enough, and with enough multifunctionality to be acceptable to the airframe designers and owners.

Lack of Alternative Sponsors (1): DoD and others are supporting IVHM research, including applications for a wide variety of nonaerospace industries. Significant industrial commitment related to this Challenge is also evident.

Appropriate Level of Risk (9): By targeting key forward-looking applications where IVHM is most likely to make a difference over the medium term, rather than focusing on solving previously unforeseen problems in existing structures by coming up with monitoring systems for them, this Challenge faces high risk.

C2 Adaptive materials and morphing structures

Use of adaptive materials and morphing structures to change the aircraft shape (outer mold lines) and functions on demand represents a revolutionary approach for enabling optimal performance over a range of flight missions. Efficient, multipoint adaptability allows optimal performance for a variety of diverse, often contradictory, mission objectives (Lin and Crawley, 1995). Historically, morphing devices have included retractable landing gear, flaps, slats, and spoilers, all of which allow aircraft to land at lower speeds and to cruise at higher speeds. Adaptive materials have been used to reduce vibrations, eliminate noise, or control local air flow features such as separation. More recently, wings with the ability to drastically change planform area and shape have been proposed, and a few advanced concepts have been built. Adaptive materials are important elements of a morphing aircraft structure due to their ability to change or alter material properties and structural shapes using energy inputs such as light, heat, and electric or magnetic fields. Adaptive materials include heat-activated shape memory alloys like NiTiNOL; ceramics (e.g., lead zirconate titanate); photonically activated, lightweight, flexible shape memory polymers; electrically activated piezoelectrics; and magnetorheological fluids. These materials, some of which are self-sensing and self-actuating, can be developed into motors, combined with mechanisms, or distributed as actuators to produce highly efficient, lightweight airplanes. The success of morphing designs requires new adaptive materials and mechanisms, as well as innovative aircraft designs.

Morphing aircraft predate the field of adaptive structures. Fighter aircraft with variable swept wings first appeared in the 1960s. These aircraft were required to take off and land on aircraft carriers and achieve efficient supersonic speeds, yet they weighed less than comparable aircraft with fixed-wing designs. The field of adaptive structures evolved in the 1970s with work on vibration suppression for optical devices using piezoelectric materials and continued into flutter suppression work in the 1980s, some of which was conducted at NASA Langley. More recent design and testing of adaptive aeronautical structural components, such as rotor blades, have also demonstrated promise for allied areas such as vibration and noise control.

Recent morphing wing designs include planform area changes of up to 50 percent. These concepts, along with adaptive materials, expand possibilities for advanced aircraft. This includes providing new opportunities to expand wing area on demand, providing local flow control devices for drag reduction, and reducing vibrations and noise (inside the cabin and externally). These combined and synergistic developments allow innovative aircraft designs that operate efficiently over a wide range of speeds, for example, to land at very low speeds, loiter for long periods of time, and cruise efficiently at both subsonic and supersonic speeds.

Morphing structures with adaptive materials are not limited to wing surfaces. They could also be used to enable engine inlets that dramatically reshape or alter flow characteristics over a wide range of speeds. However, this would require development of high-temperature adaptive materials. These and other applications provide opportunities for revolutionary changes in future aircraft structures, although the costs of incorporating such technology have not yet been determined.

DARPA's Morphing Aircraft Structures Program has sponsored several wind tunnel experiments at NASA Langley Research Center's Transonic Dynamics Tunnel. These tests, which cost more than $35 million, produced a wide range of experience and identified innovative aircraft and rotorcraft concepts and critical materials technologies for future work. DARPA has also sponsored flight research on morphing technologies applied at the system level. Although the results were promising, these tests also showed that the technologies relevant to this Challenge are still immature and require additional research.

Adaptive materials have received a great deal of attention during the past decade, mostly directed toward the development of piezoelectric devices (Chaplya and Carman, 2002; Ritter et al., 2000), metallic shape memory alloys (Shin et al., 2004; Lim and McDowell, 1999), and ferromagnetic actuations (e.g., both magnetostrictive (Moffett et al., 1991) and ferromagnetic shape memory alloys (Ullakko et al., 1997)). However, to date, few viable aeronautical concepts have been created. The principal missing technologies are self-actuating adaptive materials with sufficient power output per unit mass and new materials that can be easily molded and remolded, stretched, or reshaped drastically. Current materials are not suitable for large actuation or elastic strains required for commercial aircraft. The requirements for load-carrying efficiency (high stiffness) and actuatable structures (low stiffness) have resulted in quick fixes using stiffened polymers as wing panels.

Morphing designs that change the aircraft shape require (1) development of new materials that can be turned on and off and (2) integration of these materials into novel mechanisms with embedded, distributed power sources that can activate the structures and move them efficiently from one point to another. These new materials will require lifetimes comparable to those of current materials.

Advanced aircraft concepts require designers to think differently about how aircraft and systems can be designed to demonstrate lower landing speeds, higher cruise speeds, and longer ranges than are possible today. A fundamental task is to characterize the mechanical response of these inherently nonlinear materials, including hysteresis, fatigue, long-term behavior, and damage behaviors. Analysis and design tools that accurately predict these responses will open the door to even more applications of these revolutionary adaptive structural concepts that could optimize performance and expand the flight envelope. Key milestones include

- Identify new morphing missions and designs for reconfigurable civil aircraft, including supersonic aircraft with low sonic boom.
- Develop the next generation of high-strain adaptive materials or devices that can be activated and deactivated for repositioning, with actuation deformation up to 100 percent.
- Develop novel integrated adaptive materials that allow wing surfaces and fuselages (including inlets) to rapidly change shape or alter load paths.
- Conduct scaled wind tunnel and flight tests on active, morphing aircraft to enable innovative, lightweight designs.
- Develop new, structurally integrated adaptive devices for flow control on a commercial aircraft to, for example, reduce drag and improve performance in off-design conditions.
- Develop analysis and design tools that account for and accurately predict nonlinear behaviors of adaptive materials and morphing structures.

Relevance to Strategic Objectives

Capacity (9): Adaptive materials and structures have already led to innovative solutions to aeronautical problems across a broad spectrum of requirements, including ice removal and vibration reduction. Morphing civil aircraft can adapt to a wider variety of landing and cruising speeds and may be able to fly at supersonic speeds over inhabited areas with minimal sonic boom.

Safety and Reliability (3): Adaptive materials are key elements of some aeronautical health monitoring concepts. Morphing airliners might also allow damaged aircraft to be reconfigured for safe flight.

Efficiency and Performance (9): Adaptive materials, as part of flow control devices and seamless control surfaces, can enhance wing lift. Morphing civil aircraft would be able to reconfigure for optimal performance at various altitudes, weights, and speeds.

Energy and the Environment (3): Adaptive materials reduce fuselage noise and drag, which indirectly reduces emissions. Active vibration suppression has been successful in reducing rotorcraft noise.

Synergies with National and Homeland Security (9): Adaptive materials and structures allow aircraft to perform tasks that are difficult or impossible for conventional aircraft, such as vibration control. Morphing aircraft are high on the DoD future concepts list because of their ability to adapt to unforeseen situations, to reduce the number of aircraft required for certain missions, and to operate over a wide range of conditions.

Support to Space (3): Adaptive materials have been used for vibration control for payloads delivered to space, for opening solar arrays from compact packages, and as adaptive optics.

Why NASA?

Supporting Infrastructure (9): NASA has historically supported this type of technology and has a strong cadre of researchers with capabilities in flow control devices and adaptive materials. NASA has flight test organizations and facilities that uniquely support this type of activity. NASA Langley also has personnel developing new adaptive materials, including high-deformation piezoelectric actuators and piezo-fiber composites. More recently NASA Glenn has been developing high-temperature adaptive materials (e.g., piezoelectric and ternary nickel-titanium shape memory alloys).

Mission Alignment (9): This Challenge is very relevant to NASA's mission.

Lack of Alternative Sponsors (1): Morphing structures and adaptive materials are currently being studied by academia and the DoD.

Appropriate Level of Risk (9): Some technologies related to this Challenge face very high risk, as evidenced by DARPA interest. However, recent government-sponsored research has reduced risk and clearly identified high-risk investments and issues in materials and structures that are appropriate for NASA to pursue.

C3 Multidisciplinary analysis, design, and optimization

Methods for simulation-based, multidisciplinary design and optimization (MDO) are at the very core of a philosophy that moves away from the build-test-build approach, which has proven to be expensive and ineffective in exploring the aeronautical design space. MDO processes develop synergistic benefits by integrating people, analytical tools, experimentation, and information to design complex structural components and systems that are characterized by strong interactions. These approaches allow for development of optimal configurations, topologies, and dimensions for structural members and components to achieve design objectives, and they permit designers to examine the myriad what-ifs that characterize sophisticated designs with interdisciplinary trade-offs (Sobieszczanksi-Sobieski and Haftka, 1997).

Tools and platforms to enable the effective integration of analysis methods for the study of multidisciplinary interactions in structural design are the focus of this Challenge. A systematic analysis of uncertainty in all aspects of the design process is also important, as is increasing the level of detail in representing the structure. Uncertainties surrounding the predictive capabilities of physics-based models used in design—and their propagation in coupled systems—must be systematically included in the design process. Such design tools would greatly facilitate the process of sorting through design options and help identify and exploit interactions among multiple disciplines involved in the design process. The availability of MDO processes and analytical techniques enables experienced designers to collaborate with skilled analysts to identify and create innovative structural designs.

The rapid development of aerospace technologies has resulted in many new possibilities for aircraft design. Unfortunately, the benefit of these technologies, whether applied to conventional or radically new designs, is often slow to appear. MDO processes allow for the rapid identification of game-changing designs and design features, with significant potential impact on structural and material issues related to the design of a new generation of aerospace vehicles. The systematic inclusion of the effects of uncertainty, whether in loading, material behavior, or mission requirements, yields a rational approach for quantifying the risk associated with a certain design and allow for meaningful study of trade-offs among competing concepts. Inclusion of risk and reliability analysis in the design provides a time-dependent description of risk associated with structural and material systems in service, facilitating decisions that enhance vehicle availability and reliability.

After almost two decades of R&D, MDO processes for conventional designs have reached a high level of sophistication. In structural designs where the topology or outer mold lines are defined, a high level of success can be achieved by coupling analytical methods such as the structural finite-element technique with similar tools for load assessment. However, for designs with a multiplicity of topologies, some of which are not well-defined, and for problems where a large number of design parameters and constraints must be considered in the early stages of the design process, MDO methodologies are still underdeveloped (Giesing and Barthelemy, 1998). Major effort must also be directed at including the effects of uncertainty in the design process, as well as increasing the level of detail in representing the structure. Risk- and reliability-based design has emerged as a key research area, with industry, government, and academia focusing on developing robust methods that transition deterministic design tools to a nondeterministic environment. This effort has been primarily confined to disciplinary design with a dual focus: (1) developing approaches for modeling uncertainty in problem parameters and (2) seeking an efficient adaptation of design tools that account for the modeled uncertainties in a formal design process. New ways of formulating problems that incorporate quantitative reliability measures to facilitate effective design decisions have already been considered in this context. The extension of these approaches to large-scale structural and material design problems represents an entirely different level of problem complexity.

Significant new developments are required in both the platforms and the embedded tools that constitute the MDO process. Efficiency and effectiveness of the search process continue to be a problem, particularly in large-dimensionality problems and multimodal or disjointed search spaces. Existing problem formulations and search processes do not naturally allow for the emergence of radical design concepts and the associated design constraints. Current platforms are ill equipped to efficiently parse the vast amounts of data associated with the design process. Furthermore, not all methods are ideal for all problems. The goal of this Challenge is not to generate one perfect, all-encompassing algorithm but to use the most efficient and effective method or combination of methods for each problem. Proper algorithm selection in itself is an important research topic. There is a marked need for developing analysis modules for the search process to query. Some structural design issues, such as manufacturability, cost, repair, and environmental impact, are seldom represented in the design process. These analysis tools must be developed at multiple levels of granularity and precision, to coincide with the appropriate stage of the design process. The numerical efficiency of these tools is paramount, and alternative paradigms that take advantage of a new generation of parallel computational hardware must be sought (Giesing and Barthelemy, 1998; Sobieszczanksi-Sobieski and Haftka, 1997). Furthermore, existing analysis tools lack quantitative measures of prediction uncertainty. Uncertainty modeling in a data-lean environment, specifically for new concepts, continues to be an issue in this regard. There is a similar dearth of computationally efficient methods for reliability assessment, particularly in situations where uncertainty distributions do not conform to standard forms or where components or elements exhibit discrete behavior. The propagation of uncertainty in complex and highly coupled multidisciplinary systems needs to modeled, and tools for design and optimization in a nondeterministic environment continue to be computationally intractable, especially when applied to design problems involving a large number of nondeterministic variables, parameters, and design constraints.

New search methods and platforms that allow for an effective integration of analysis tools are required for the design of the next generation of aerospace structural and material systems. These methods would incorporate effective and computationally efficient procedures and tools for quantifying risk and would be integrated with design optimization and decision-making tools and software at all levels of the design process. A systematic approach for modeling risk and uncertainty in complex coupled systems should be a key concern in this area of inquiry. Use of commercial tools in optimization is not enough to advance the state of the art in MDO. Optimization is only one piece of the analysis, design, and optimization triad. It is the tightly integrated development of analysis and optimization tools that furthers the potential of MDO methods. In the aerospace arena, such expertise is unique to NASA—additional gains can be realized with NASA working in close collaboration with researchers from academia and industry. A number of synergistic benefits could also be achieved by developing this approach in concert with health-monitoring technologies (see R&T Challenge C1). Key milestones include

- Develop multidisciplinary analysis tools that incorporate aerodynamics, structural dynamics, vibration, thermal response, and acoustic response with structural response to mechanical loads.
- Extend multidisciplinary tools to incorporate explicit mathematical modeling of design issues such as manufacturing processes, life-cycle cost, and repairability.
- Develop efficient approaches for multivariable optimization.
- Develop efficient and effective search processes for analysis of large complex systems.
- Develop approaches for modeling uncertainty in data-lean environments.
- Develop computationally efficient methods for reliability assessment.
- Develop systematic approach for modeling risk and uncertainty in complex coupled systems.

Relevance to Strategic Objectives

Capacity (9): This Challenge would support the development of new vehicle concepts and designs that are more efficient from the standpoint of speed, payload capacity, and fuel burn. The formal inclusion of multiple design objectives would permit the development of vehicles capable of operating in multiple operating environments and could alleviate traffic congestion in busy air corridors.

Safety and Reliability (3): Quantitative inclusion of risk and uncertainty in the design process could result in structural designs that promote vehicle safety and reliability. Temporal estimates of structural reliability might allow for improved practices in airframe maintenance and repair.

Efficiency and Performance (9): This Challenge will support development of structural components and systems that exploit synergistic benefits of multidisciplinary interactions to optimize explicit design criteria related to efficiency and performance.

Energy and the Environment (1): Lightweight structures would probably increase payload capacity but not necessarily reduce fuel burn of particular vehicles. MDO can increase understanding of structural acoustics and noise due to airflow, vibration, and structural dynamics but would not necessarily offer any solutions.

Synergies with National and Homeland Security (3): This Challenge would also improve the design and development of military aircraft.

Support to Space (3): The design of space structures has many of the same multidisciplinary elements as the design of advanced aircraft. The inclusion of quantitative measures of risk in the design decision process would be of particular relevance to the design of space structures.

Why NASA?

Supporting Infrastructure (9): MDO tools and processes have a history of healthy development at the NASA centers. The multidisciplinary expertise required for the development of relevant platforms and tools—disciplinary experts, experimental facilities, and information technology support—are all available at NASA. Furthermore, NASA is uniquely qualified to conduct MDO research with aeronautics applications in mind.

Mission Alignment (9): This Challenge is very relevant to NASA's mission; it is a cross-cutting, enabling technology that supports many NASA missions.

Lack of Alternative Sponsors (3): Some support for this activity exists within the DoD and the aerospace industry, but there is a lack of infrastructure or research leadership in this area at these other agencies and organizations. Arguably, commercial tool set providers may be able to better accomplish this challenge.

Appropriate Level of Risk (9): This Challenge faces moderate risk. The research tasks are all plausible but not routine and would require NASA researchers to collaborate with academia and industry.

C4 Next-generation polymers and composites

Over the past 50 years, polymeric composites have revolutionized and improved the performance of aircraft structures. Future needs for enhanced structural performance, high-temperature capability, and durability can only be met by the next generation of high-temperature, polymer-based composites. Next-generation composites will take advantage of improved polymeric matrices, new reinforcement materials, hybrid reinforcement approaches, improved joining technology, and science-based manufacturing with controlled three-dimensional placement of reinforcements. They will potentially lead to significant improvements in structural efficiency, safety, and high-temperature performance, as well as a reduction in data scatter, increased damage tolerance (e.g., resistance to delamination), and improved manufacturability (elimination of hand lay-up). These composites will likely incorporate adaptive materials and multifunctional concepts, thus serving as enabling materials for visionary concepts in nacelle components, wing structures, and fuselage materials.

Relevant research is currently directed toward development of higher temperature matrix materials; nanoscale reinforcements such as nanofibers, nanoclays, and carbon nanotubes; composites with multiple, different reinforcement fibers, and integration of adaptive materials to increase functionality. These materials have potential application in propulsion systems and for supersonic aircraft. Multiscale modeling efforts are also being conducted to guide the design and development of these materials across the nano-micro-meso structural levels.

The development of next-generation composites requires three capabilities to gain a complete understanding of the potential advantages of these materials: multiscale modeling, science-based processing techniques, and structural and mechanical testing. Multiscale models that link nano- and microstructure to structural composite response as well as the introduction of hybrid and multifunctional models are a critical concern. Research should also target (1) development of science-based processing techniques that account for resin chemistry, cure kinetics, and flow physics in guiding placement and distribution of the different reinforcement phases and (2) optimization of the reinforcement–matrix interface. Finally, structural and mechanical testing capabilities are needed to evaluate both the design and processing parameters. These three capabilities will enable the creation of effective life-prediction models and thereby eliminate statistical variation and defects. Key milestones include

- Demonstrate fabrication of composites with multiple different reinforcement fibers.
- Integrate adaptive materials to increase functionality.
- Develop techniques for manufacturing, processing, and dispersion of nanoscale reinforcements.
- Develop a fundamental understanding of how different kinds of reinforcements (e.g., nano, functional, or hybrid additives) affect the performance of polymers and composites.
- Improve damage tolerance for high-temperature polymers.
- Develop effective life-prediction models for polymers and composites.
- Investigate environment-friendly end-of-life reuse or disposal strategies.

Relevance to Strategic Objectives

Capacity (9): This Challenge has the potential to reduce structural weight, increase strength, and enable higher temperature multifunctional structures that will enable new vehicle concepts and increase capacity.

Safety and Reliability (3): Advanced composites will have improved damage tolerance, reduced delamination, and improved crashworthiness, which will moderately improve overall aircraft safety and reliability.

Efficiency and Performance (9): This Challenge has the potential to increase structural efficiency, increase aircraft range, increase the use of polymers in engine applications, and facilitate the development of advanced aircraft, such as an economically viable commercial supersonic aircraft.

Energy and the Environment (1): This Challenge contributes to this objective only indirectly, via improved structural efficiency.

Synergies with National and Homeland Security (9): Polymers and composites continue to be important for many DoD and DHS applications.

Support to Space (3): High-temperature polymeric composites are important for some space applications.

Why NASA?

Supporting Infrastructure (9): NASA (particularly at Langley) has excellent infrastructure for composites research, including development of methodologies to deal with damage tolerance and fracture mechanics. These efforts are particularly important because composites do not conform to linear damage theory. Nanocomposite efforts at Glenn have been initiated and are focusing on high-temperature polymers.

Mission Alignment (9): This Challenge is very relevant to NASA's mission to develop new materials with improved structural performance and reduced weight.

Lack of Alternative Sponsors (1): DoD funded the first generation of composite materials, although it is not currently funding basic composites research. Industry has sponsored relevant research in recent years.

Appropriate Level of Risk (9): The level of risk is high. Fundamental research has been conducted at universities and government laboratories, but only at the small coupon level.

C5 Noise prediction and suppression

At this time, many passive and active control concepts are being pursued to control the interior and exterior noise of aircraft, including rotorcraft, over a wide range of flight regimes. However, efficient solutions have not yet been achieved. Local communities in this country and abroad are becoming extremely aggressive in passing stringent noise regulations. As a result, landings and take offs at many airports have been restricted. Complying with additional noise restrictions could impose an enormous weight penalty on many aircraft. Additionally, the flight envelope is often restricted to keep noise within acceptable limits. Regulations pertaining to noise levels have limited civil applications of helicopters even at conventional airports because rotorcraft are noisier than most commercial aircraft. In addition, lack of public acceptance has been a major barrier to the widespread commercial use of helicopters to serve off-airport locations. Efficient methods to reduce noise will help expand the use of rotorcraft and fuel-efficient prop-rotor aircraft in commercial operations and increase the capacity of the air transportation system.

Reliable noise predictions are required to design efficient passive and active noise suppression devices. The problem is multidisciplinary, but with an important structural component. Advanced tools are required to accurately predict and alleviate noise, especially the aeroacoustic noise of rotorcraft. Research is needed to better understand the basic mechanisms of exterior and interior aircraft noise generation for different flight conditions. Current prediction tools for structurally transmitted noise are either finite-element-based (and therefore applicable only in the lower frequency range) or are energy- or power-based (covering a wider frequency range but with limited accuracy). Effective noise control techniques must take into account multiple types of aerodynamic and acoustic excitations. Therefore, structural prediction tools must be integrated with computational aeroacoustic and fluid dynamic prediction tools for a fully coupled solution to the problem of structural noise.

Suppression of exterior aircraft noise using smart materials holds great potential, but much R&D is needed. Advanced materials for larger, stronger fan blades and higher-temperature turbine blades, together with the development of very-high-bypass-ratio engines, is the biggest single factor in reducing external noise produced by jet aircraft. Good payoff can be achieved by developing locally morphing structures that smartly deploy themselves as needed, to reduce the noise generated by the propulsion system as well as the airframe. Variable-geometry-chevron nozzles, which could be driven by the shape memory alloy NiTiNOL, have been demonstrated to provide reduced noise during takeoff and then reconfigure themselves to a more efficient shape for cruise (Calkins and Butler, 2004). Smart materials can also be used to make fan duct liners that can adapt themselves (by changing cavity depth, face sheet porosity, etc.) according to the fan operating conditions to maximize noise reduction. Similar concepts can be applied to airframe noise suppression, where smart morphing structures could be integrated with noise reduction devices installed on aircraft high-lift systems (flaps and slats). These devices would operate at normal landing and takeoff conditions for noise reduction but could rapidly retract (or change configuration) as needed to increase lift and power during an emergency to maximize aircraft performance.

Noise experienced by flight crew and passengers is due largely to the excitation of the fuselage by the exterior flow. The fuselage structural design plays a key role in determining the amount of add-on noise control treatment needed to meet interior noise goals. Major strides in controlling noise in the aircraft cabin can be achieved using advanced structures and materials techniques.

The use of lightweight composite structural designs in commercial aircraft has greatly increased over the last few years. Unlike metallic structures, composite structures are excellent radiators of noise. Structural tuning concepts such as those pioneered in NASA-funded research for the reduction of turboprop tones may provide new opportunities to reduce noise while maintaining the strength and weight benefits of composite material systems. Experiments on current composite fuselage designs show that they would benefit from composite material systems with higher intrinsic damping. Work is needed to balance the structural and noise reduction requirements of honeycomb structures. Experiments have shown that partially filling cells with small loose particles can increase the damping properties of honeycomb panels. Other promising approaches include tailored lay-up using high-damping composite materials; nanotechnology to enhance structural damping; new acoustic and thermal insulation; morphing or tailored structures for achieving laminar flow and noise control; multifunctional composite structures (which offer improved noise control, strength, health monitoring, thermal insulation, and so on); and smart materials employing nanobiotechnology that can sense and respond to acoustic, elastic, thermal, and chemical fields in a positive, human-like manner. Key milestones include

- Measure noise signatures in controlled environments such as anechoic wind tunnels, for a range of flight conditions.
- Predict noise signatures using advanced multidisciplinary methodologies, validating against test data for level and maneuvering flight modes.
- Develop efficient structural solutions for interior noise control, i.e., structural optimization.
- Design non-load-bearing passive noise control.
- Design active controls for interior and exterior noise through smart structures technology.
- Develop low-noise rotors.
- Selectively flight test full-scale systems with noise signature measurement.

Relevance to Strategic Objectives

Capacity (9): Efficient suppression of noise would help to expand the flight envelope, including forward speed, rate of climb, descent, and flight course. Additionally, it would help to develop advanced vehicle concepts and next-generation heavy-lift rotorcraft. This will be a key step toward runway-independent aircraft for civil operations.

Safety and Reliability (1): This Challenge will have little impact on this Objective.

Efficiency and Performance (3): Efficient passive and active noise suppression devices could help to increase the flight envelope, particularly in congested areas.

Energy and the Environment (9): Reducing exterior noise will reduce the environmental impact of aviation.

Synergies with National and Homeland Security (3): Noise suppression will help to develop stealth vehicles, which is a key mission of DoD. In addition, noise suppression will enable increased use of military aircraft on bases near population centers.[5]

Support to Space (1): This Challenge would provide limited benefits to space operations.

Why NASA?

Supporting Infrastructure (9): NASA has some unique experimental facilities to measure noise signatures, including the 20 × 24 × 30 ft Anechoic Quiet Flow Facility, the 27.5 × 27 × 24 ft Anechoic Noise Facility, and the 21 × 31 × 15 ft Reverberation Chamber at Langley, and the 40 × 80 ft/80 × 120 ft wind tunnel with acoustic lining at Ames.

Mission Alignment (9): This Challenge is very relevant to NASA's mission.

Lack of Alternative Sponsors (3): Prediction and measurement of noise is of low priority for industry. Also, industry infrastructure is inadequate for long-term systematic studies. There are some limited research activities in DoD laboratories.

Appropriate Level of Risk (9): This Challenge faces moderate to high risks.

C6a Innovative high-temperature metals and environmental coatings

The goal of this Challenge is to provide the underlying technologies for materials modeling tools that can predict properties of new high-temperature metallic materials and associated protective coatings. The effort would include generation of the necessary fundamental data, complemented by testing that simulates realistic jet engine operating conditions to validate the models. These tools would then be applied, in concert with industry, to the development of innovative propulsion materials. Typically, substrate materials are developed separately from environmental coatings and then integrated toward the end of the development program, or coating development follows substrate development. This stretches development time considerably, often to a decade or more. These modeling tools are expected to reduce development time for high-temperature materials and coatings by 50 percent (NRC, 2004).

Advanced high-temperature materials are critical to advancing the next generation of jet engines that will power subsonic and supersonic fixed-wing aircraft, while enabling reduced operating costs and improved engine safety and reliability. Improved metallic alloys are needed for high-temperature structural applications such as turbine disks, blades, and pressure cases. Increases in operating temperature of 50°C or more for jet engine parts is possible, but the length of time and cost to develop these materials, and the risk that success will not be achieved, have been a huge disincentive to aggressive development of innovative materials.

The abilities to estimate materials properties and model complex phase fields, microstructures, and materials processing are advancing through the use of new computational tools and powerful desktop computers. However, application of this work to guide materials research is still in the beginning stages. NASA has the opportunity to be a leader in this technology.

The key to improving engine efficiency lies in developing turbine materials systems (i.e., alloy substrates for the turbine blade, disk, and shroud, plus necessary environmental coatings) that possess structural performance at higher temperatures while maintaining stability for tens of thousands of operating hours within an environment that is highly oxidative, corrosive, and erosive. Long development times would be reduced by the ability to conduct many experiments computationally, analogous to what is currently done by the tools for computational fluid dynamics. Key milestones include

- Define required models and a model integration strategy to provide necessary functionality for simulations.
- Select models for further development, based in part on how well they are aligned with materials systems that provide greatest benefit for propulsion systems.
- Develop models for selected substrates and associated environmental coatings; determine all the physical parameters required by the models.
- Validate the models by applying them to the development of new materials that are selected in concert with industry.

Relevance to Strategic Objectives

Capacity (3): Advanced high-temperature alloys with environmental protective coatings are one enabler for supersonic flight. These materials will increase maintenance intervals and could contribute to more flexible flight operations. Materials modeling will enable these materials to be developed faster, at lower risk.

Safety and Reliability (9): This Challenge will resolve safety and reliability issues with engines that operate at higher temperatures by improving the inherent capability of materials to withstand degradation modes.

Efficiency and Performance (3): Higher-temperature materials will directly improve the aerothermodynamic efficiency of the engine, thereby reducing fuel burn. These materials also reduce maintenance costs. Higher temperature materials will enable supersonic propulsion systems. The

[5] R. Flater, American Helicopter Society, Testimony before the House Armed Services Committee, Subcommittee on Tactical Air and Land Forces, 108th Congress, March 12, 2003. Available at http://vtol.org/pdf/congr03.pdf.

next generation of a turbine materials system resulting from this Challenge is anticipated to increase operating temperatures by about 50°F within 5-10 years, resulting in only a moderate impact on this Objective.

Energy and the Environment (1): This Challenge has little impact on this Objective.

Synergies with National and Homeland Security (9): This Challenge would benefit efforts by DoD to develop improved, long-life propulsion systems for supersonic and hypersonic flight.

Support to Space (3): This Challenge would benefit efforts to develop air-breathing access-to-space turbine engines. Advanced modeling tools might be used to guide development of specialized alloys expressly tailored for space launch systems.

Why NASA?

Supporting Infrastructure (9): NASA Glenn Research Center has a cadre of experts in the modeling and development of advanced turbine alloys and coatings. NASA Glenn also posseses unique specialized testing capabilities that simulate severe engine conditions, such as foreign object damage, creep, fatigue, and various environmental conditions. NASA also has outstanding electron microscopy equipment and facilities for high-temperature materials characterization.

Mission Alignment (9): This Challenge is very relevant to NASA's mission. In the past, NASA contributed significantly to this field.

Lack of Alternative Sponsors (3): The Air Force, Navy, and DARPA have all conducted work related to this Challenge. However, the DoD effort is not aimed at commercial engine or rotorcraft applications and is only likely to fund point solutions to specific problems.

Appropriate Level of Risk (9): This Challenges faces high risk.

C6b Innovative load suppression, and vibration and aeromechanical stability control

Because the aerodynamic environment surrounding an aircraft is unsteady, the aircraft experiences significant vibratory loads that need to be either isolated or absorbed to minimize their impact on passengers and key structural components and instruments. Also, unsteady aerodynamic forces couple with structural and inertial forces, resulting in potentially catastrophic aeromechanical instabilities. This Challenge will minimize the impact of vibratory loads using innovative passive and active techniques. It will also examine innovative techniques to increase the aeromechanical stability margins of aircraft in all flight modes. Minimizing vibratory loads enhances ride quality, increases the structural life of components, and improves handling. Aeromechanical stability (aeroservothermoelasticity) is the key to expanding the flight envelope.

Current aircraft use numerous passive devices to isolate or absorb loads. Prediction of vibratory loads, especially in rotorcraft, is far from satisfactory. Mechanisms of vibration in maneuvering flight are not completely understood. Vibration is a nonlinear-coupled phenomena that involves unsteady aerodynamics and wakes; nonlinear structural deformations and inertial couplings; and interactions between the flow and the structure. Aeromechanical stability can be a major issue with new configurations and expansions to the flight envelope.

Advanced CFD methodology needs to be coordinated with (1) comprehensive structural analyses to predict aeromechanical stability, vibratory loads, and vibration signatures at different stations in the airframe and (2) systematic validation against test data. The development of comprehensive MDO studies focused on inherently stable, low-vibration aircraft is another area worthy of research. Experimental issues involve the performance of systematic wind tunnel and flight tests using dynamically scaled and full-scale models. Problems also stem from a fundamental mismatch in basic structural models and reduced-order control models. Key milestones include

- Predict vibration using advanced CFD methodologies and validate experimentally.
- Predict aeromechanical stability for advanced configurations and expanded flight envelope (including hypersonic flight) and validate experimentally.
- Measure vibratory loads and vibration signatures under controlled wind tunnel environments for a range of flight conditions.
- Develop novel techniques for control-oriented modeling.
- Selectively flight-test full-scale systems, measuring vibration signatures and damping levels at level and maneuvering flight conditions.
- Innovate and employ active or passive techniques to minimize vibration and increase stability margin.
- Develop MDO techniques to develop low-vibration, stable systems.

Relevance to Strategic Objectives

Capacity (3): This Challenge would help increase payload and expand the flight envelope.

Safety and Reliability (9): Minimizing vibratory loads will increase structural life of components and improve reliability of controls and instrumentations. Aeromechanical stability margins are important for flight safety.

Efficiency and Performance (3): Increased stability margins would result in moderate increases in airspeed, payload, and structural efficiency.

Energy and the Environment (1): Reducing vibratory loads might have some impact on noise, but the effect would be minimal.

Synergies with National and Homeland Security (9): Vibratory loads have direct impact on DoD missions, especially the accuracy of some aircraft weapons. This Challenge would also increase the life of structural components and would help increase the maneuverability of military aircraft.

Support to Space (3): Active and passive vibration suppression techniques and stability augmentations could also apply to vibration suppression for access-to-space vehicles.

Why NASA?

Supporting Infrastructure (9): NASA has unique experimental facilities that are important for full-scale and small-scale model testing. These include the 40 × 80 ft/80 × 120 ft Wind Tunnels at the National Full-Scale Aerodynamics Complex at Ames and the Transonic Dynamics Tunnel at Langley for Froude- and Mach-scale testing.

Mission Alignment (9): This Challenge is very relevant to NASA's mission to improve aircraft performance.

Lack of Alternative Sponsors (3): Prediction and understanding of vibration and aeromechanical stability is already of moderate priority to industry and DoD.

Appropriate Level of Risk (9): This Challenge faces moderate to high risk.

C8 Structural innovations for high-speed rotorcraft

Recently, NASA conducted a systematic preliminary design study (Johnson et al., 2006) on a high-speed, heavy-lift civil rotorcraft with a cruise speed of 250 knots (Mach 0.6). It was "neighborly" quiet, economically competitive with a Boeing 737 aircraft, flexible in cruise altitude, and runway independent. Potential rotorcraft configurations include tilt-rotor, tandem-rotor compound, and an advancing blade concept (compound coaxial rotor). The development of a next-generation, cost-effective, high-speed rotorcraft that can meet these technology goals, faces numerous difficulties and barriers, which include scaling effects, aeromechanical efficiency, power-train limitations, structural efficiency, and life-cycle cost. Overcoming this Challenge will be a giant step toward the development of a runway independent aircraft that can efficiently expand capacity.

For the development of a high-speed, heavy-lift, efficient rotorcraft, a multidisciplinary aeromechanics research program needs to be established. It should encompass innovative rotor designs, active vibration and load control, variable-speed rotor technologies, active noise control, rotor morphing, lightweight and crash-absorbing airframe technologies, advanced variable-speed transmission systems, diagnostics and prognostics of drive trains and rotor head systems, increased autonomy and maneuverability, and enhanced handling quality. Because of an enormous increase of dynamic loads at high-speed flight (due to increased aerodynamic asymmetry), advanced composite designs with high damage tolerance are key structural issues. This provides opportunities to incorporate many disruptive and nondisruptive technologies in rotorcraft design, with an enormous payoff in performance and life-cycle cost compared with existing helicopters. Key milestones include

- Develop comprehensive aeromechanic analyses for high-speed rotorcraft that include tilt-rotor, tandem-rotor compound, and compound coaxial rotors for level and maneuvering flight conditions.
- Develop aeromechanics and technology tools for the drive-train system and other key components necessary for variable-speed rotors.
- Design and develop lightweight, crash-absorbing composite airframes.
- Develop technology for all-weather rotorcraft operation.
- Develop advanced composites with high damage tolerance for use in large dynamic structural components.
- Reduce required shaft power by 15 percent from current levels using elastically tailored composite blades, active structural and flow control, and advanced airfoils.
- Reduce life-cycle cost using health and usage management systems, low-cost tailored airframes, and lightweight low-vibration rotors.

Relevance to Strategic Objectives

Capacity (9): The performance of a next-generation, revolutionary civil rotorcraft greatly increases the capacity of the air transportation system.

Safety and Reliability (1): This Challenge involves the use of many disruptive technologies and is unlikely to significantly increase safety or reliability.

Efficiency and Performance (3): This Challenge would increase the speed, range, payload, and structural efficiency of rotorcraft.

Energy and the Environment (1): A next-generation rotorcraft should be designed to fly at an altitude of 15,000 ft or higher, to reduce noise on the ground. A variable-speed rotor could also be used to reduce external noise. However, although these efforts would reduce the noise produced by rotorcraft, it would only reduce them to levels comparable to fixed-wing aircraft. Therefore this Challenge will not reduce the overall noise produced by the air transportation system.

Synergies with National and Homeland Security (9): High-lift, high-speed rotorcraft will have an enormous impact on emergency evacuation, heavy-lift operations, and other military applications.

Support to Space (1): This Challenge is not relevant to this Objective.

Why NASA?

Supporting Infrastructure (9): NASA has unique experimental facilities that are important to rotorcraft full-scale and small-scale testing. These include the 40 × 80 ft/80 × 120 ft

Wind Tunnels at the National Full-Scale Aerodynamics Complex at Ames, the Drop Test Facility and Transonic Dynamics Tunnel for Froude- and Mach-scale rotor testing at Langley, and the Power-Train Full-Scale Test Facility at Glenn.

Mission Alignment (9): This Challenge is very relevant to NASA's mission to improve aircraft performance.

Lack of Alternative Sponsors (3): The U.S. Army is the primary supporter of research on high-speed rotorcraft, but the Army will not investigate issues related to civil applications.

Appropriate Level of Risk (9): This Challenge faces high risk.

C9 High-temperature ceramics and coatings

Advanced structural ceramics, including oxide-, carbide-, nitride-, and boride-based systems, are characterized by high strength, stiffness, hardness, corrosion resistance, and durability. Furthermore, they retain these properties at high temperatures, making them ideal for a wide range of demanding applications, including engine components for subsonic aircraft (combustor liners, exhaust-washed structures, high-temperature ducts, heat exchangers, and nacelle insulation) and airframe and propulsion systems for high-speed vehicles. Due to their inherent brittleness and low fracture toughness at ambient conditions, they are often combined with other materials to produce composite systems that take advantage of the high strength of small-diameter ceramic fiber reinforcements or used as nonstructural coatings for thermal management. In general, each class of material exhibits inherent benefits and limitations for particular use environments (NRC, 1998).

The primary benefit of structural ceramic materials is increased thermal capability, which improves propulsion system efficiency, increases lifetime, enables higher operating speeds, and expands the margin of safety in airframe applications. The selection of the ceramic system and its use temperature is dictated by the chemistry of the operating environment and the minimum acceptable lifetime of the component. Oxide composites with operating temperatures as high as 1200°C and lifetimes of thousands of hours in highly oxidizing combustion or reentry environments are very suitable for some engine components, warm structures, and thermal management components.

Nonoxide composites made of silicon carbide reinforced either with carbon fibers or a combination of carbon fibers and silicon carbide fibers are capable of operating temperatures of 1300°C-2500°C for short times in highly oxidizing environments or for much longer times near the lower end of the thermal range when protected with coatings. Furthermore, because nonoxide fibers exhibit higher strength and better strength retention than oxide fibers, they are being widely researched for applications in combustion environments as well as for hot structures of reentry or hypersonic vehicles.

Refractory metal (e.g., hafnium or zirconium) carbides and borides are capable of surviving thermal excursions up to 2000°C-2500°C for short times with little material recession, making them strong candidates (in either monolithic form or as a composite matrix) for the sharp leading edges of hypersonic vehicles.

During the last 10 years, significant progress has been made in the processing, development, and demonstration of many ceramic systems for specific applications. Oxide composites deriving damage tolerance from highly porous matrices have been commercialized, and other systems with novel fiber coatings have been demonstrated in subscale testing for reentry vehicle thermal protection systems. Silicon carbide matrix processing approaches have advanced significantly, with systems produced by chemical vapor infiltration, melt infiltration, and preceramic polymer infiltration all having been demonstrated in subscale testing for jet or rocket engine components. NASA Glenn has led efforts to fabricate and test jet engine components such as exhaust nozzle liners, combustor liners, and turbine airfoils with silicon carbide matrix composites. Rocket nozzles fabricated from silicon carbide materials have been rig tested, and NASA Ames has demonstrated the ability to reproducibly fabricate refractory metal carbide and boride systems.

Despite the above successes, component fabrication is not often taken much beyond the prototyping stage. Fabrication methods can significantly affect material properties, but it has not been possible to devote enough effort to understanding the effect of variations. In addition, new design rules and attachment methods must be developed to fully exploit the unique properties of these materials. There has not been sufficient component testing under actual operating conditions to validate design rules, nor are there sufficient mechanical and thermal performance data to fully characterize these ceramic systems. Therefore, there is currently low confidence in designing structural components with these material systems.

Advancing the state of the art for high-temperature ceramics suitable for aeronautical applications requires research in several key areas: fabrication and testing, modeling, and attachment methods. As mentioned above, insufficient fabrication and testing experience deprives designers of confidence in the long-term behavior of these materials and in the design rules for translating material characteristics into component designs. As a consequence, structures are typically overdesigned or constrained by existing designs for other classes of materials. At best, structures are rarely optimized; at worst, they fail when the material is inappropriately applied.

Additionally, modeling tools to predict the life of components made of these materials are inadequate. This leads to inaccurate performance and cost assessments and further limits the use of ceramic materials. Since these materials are only considered for niche applications, no economics of scale can be anticipated. This problem could be alleviated to a large extent through the development of better design tools, a more thorough understanding of the effects of process variations, and more efficient commercial fabrication approaches.

Work is also needed to develop robust methods for attaching hot components to warm and cool structures and to develop textile approaches for integrating complex component architectures with key features such as stiffeners, sensors, and cooling features. Near-term milestones include

- Generate material property databases appropriate for design of a high-temperature ceramic component.
- Complete full-scale testing of at least one ceramic composite component with improved performance for subsonic aircraft applications (e.g., fairing heat shields, combustor liner, or turbine airfoil).
- Develop models to optimize a structure for a new, rather than an existing, platform.
- Model crack growth under actual operating conditions.
- Develop advanced ceramic composites for large surfaces and leading-edge components for supersonic and hypersonic vehicles and complete relevant environmental testing of subcomponents.

Far-term milestones include

- Flight test at least one ceramic composite component for improved subsonic flight vehicles and transfer the technology to industry.
- Verify model predictions of performance using flight test data.
- Extend model predictions to new flight speed regimes to optimize supersonic and hypersonic vehicle designs for hot structures and engine components.
- Demonstrate, through full-scale testing, at least one ceramic composite component for a supersonic or hypersonic platform.

Relevance to Strategic Objectives

Capacity (3): Ceramics, ceramic composites, and ceramic coatings could improve the operating temperatures of aircraft engines, leading to increased aircraft speed.

Safety and Reliability (1): This Challenge would increase safety margins for aircraft components such as nacelle insulation and burn-through shields, but the overall effect would be minor.

Efficiency and Performance (9): This Challenge would increase the operating temperatures of aircraft engines, resulting in higher efficiencies. They are an enabling technology for airframes and engines for hypersonic aircraft and would facilitate the development of commercial supersonic aircraft.

Energy and the Environment (3): High-temperature materials would enable engines to run hotter and to potentially decrease NO_x emissions.

Synergies with National and Homeland Security (3): This Challenge is relevant to military supersonic and hypersonic aircraft.

Support to Space (9): This Challenge is very relevant to access-to-space vehicles, as evidenced by the thermal protection systems developed for the space shuttle and more recent X-vehicles.

Why NASA?

Supporting Infrastructure (9): NASA Glenn has materials expertise and unique facilities in which to test the performance of ceramic engine components under appropriate flow and pressure conditions for jet aircraft engines. It also has a full suite of materials characterization facilities, and facilities to evaluate component and material behavior in rocket engine environments. NASA Ames has unique environmental exposure facilities and arc jet tunnels capable of simulating hypersonic and reentry environments.

Mission Alignment (9): The development of high-temperature, ceramics-based systems is very relevant to NASA's space exploration mission.

Lack of Alternative Sponsors (3): DoD continues to support relevant research. However, NASA is still positioned to lead in the development of these materials for the most extreme conditions.

Appropriate Level of Risk (9): This Challenge faces high risk.

C10 Multifunctional materials

Materials that possess multifunctional behavior combine electronic, magnetic, chemical, thermal, and mechanical properties at the macro, micro, or atomic level. These materials present unique opportunities for integrating communication, actuation, sensing, self-healing, and energy-harvesting functionalities into lightweight, load-bearing structures. Multifunctional materials enable a wide range of benefits, including improved aircraft telecommunications (wired, wireless, and optical); enhanced potential capabilities and flexibility for electronic and optoelectronic platforms, such as agile phased-array and multifunctional radar systems; structural prognosis and nondestructive evaluation; self-sensing and self-repair; camouflage and avoidance; and local power generation though energy harvesting. The use of structural elements to provide new functions to aircraft platforms increases structural efficiency and enables new aircraft capabilities.

A number of multifunctional concepts have been demonstrated, such as the conformal load-bearing antennas implemented in military vehicles. Additional work on materials capable of self-healing and local power generation has been conducted and is being integrated into research aircraft. The first use of multifunctional materials in operational aircraft will likely occur in UAVs, where consequences of failure are low and issues such as energy harvesting are important. While the majority of research to date has been confined to coupled electromechanical domains, a much broader vision is possible. Recent discoveries of electrochromic, magnetoelectric, and thermomechanical materials show substantial promise for future multifunctional materials.

From a programmatic viewpoint, the research problems inherently involve multiple domains and require a multiphysics (electrical, magnetic, chemical, structural, thermal, and electromagnetic) approach. Additionally, facilities to fabricate and test either monolithic or composite multifunctional materials are rare. The main tasks are to develop new materials based on fundamentals or to design composite materials that couple functionality without disrupting structural performance. To date, little research has been conducted at the atomic or composite levels, with even less on fabrication and testing. Relevant research should be conducted in collaborative between universities and NASA. Key milestones include

- Develop a comprehensive analysis to predict the performance of selected monolithic and composite multifunctional materials.
- Use this analysis to guide parametric studies to explore and optimize material response with the goal of understanding the combined response of the multifunctional material.
- Fabricate materials according to model predictions.
- Evaluate material performance, both coupled and structural, and compare with analytical predictions.
- Integrate multifunctional materials into a structural component for benchtop verification.
- Conduct flight tests on a structural component.

Relevance to Strategic Objectives

Capacity (3): Multifunctional materials can increase the payload fraction of individual aircraft via improved structural efficiency, allowing a given airplane to carry more passengers or cargo.

Safety and Reliability (3): Multifunctional materials potentially increase aircraft safety and reliability. For example, self-healing structures provide the opportunity for in-flight repair.

Efficiency and Performance (9): Multifunctional materials can improve the efficiency of engines by evaluating the flow characteristics at or near the engine inlets and outlets and provide locally generated power by converting thermal energy into electrical energy.

Energy and the Environment (3): Multifunctional materials can harvest energy from the surrounding environment, by converting solar, mechanical, or thermal power into electrical power.

Synergies with National and Homeland Security (9): This Challenge is very relevant to remote observation, hypersonic flight, and aircraft protection (through radar absorption or cloaking).

Support to Space (9): Multifunctional materials support access to space by enabling structures with inherent sensing capabilities that can transmit data to a central location.

Why NASA?

Supporting Infrastructure (3): NASA facilities at both the Langley and Glenn research centers are very relevant to this Challenge. Langley has developed relevant expertise through a recent morphing program. However, academia and the DoD possess similar facilities.

Mission Alignment (9): This Challenge is very relevant to NASA's mission to conduct fundamental aeronautics research.

Lack of Alternative Sponsors (3): DoD is interested in relevant research but not in applications to civil aviation. University-funded research in this area has demonstrated the viability of these materials but has not yet explored their relationship to aircraft systems.

Appropriate Level of Risk (9): Relevant technologies are still very immature, and this Challenge faces high risk.

C11 Novel coatings

Exterior and interior coatings can be designed to provide novel, yet beneficial functionality through the use of nanoscale fillers or self-assembled monolayers. Advanced coatings are attractive since they can be applied to existing structural components as an add-on technology.

This is a broad Challenge that may enable visionary concepts in aircraft design and improve structural efficiency and safety. Potential benefits include self-assembled monolayers for corrosion protection, soft polymeric coatings for noise reduction, ultrahydrophobic surfaces for drag reduction, coatings that enable aircraft to shed or melt ice without the use of deicing fluids, nanoparticle-filled coatings for wear resistance, electrically conductive coatings, and self-sensing and self-repairing surfaces. Development of novel coatings is an active research area in both academia and industry, but there is not a lot of research targeted at aeronautics or aerospace applications. Many potential systems have been demonstrated in the laboratory environment, for example, self-assembled monolayers for corrosion protection—while many others, such as deicing coatings, are under more advanced development. Key barriers for these coatings include development of nanoscale fillers with the appropriate functionality, processing and dispersion of nanoscale fillers, and the high cost of many nanoscale fillers (e.g., carbon nanotubes). In addition, most of the coatings (e.g., self-assembled monolayers) need to scale up for use with larger structures such as an aircraft wing. Finally, most of the coatings are not yet durable enough to be used in aeronautical applications.

Novel coatings are an emerging field with significant opportunity for new materials to achieve the various functions described above. Key milestones include

- Develop more durable, environmentally stable formulations for novel coatings that can survive in an aircraft environment.
- Develop cost-effective methods of processing and applying novel coatings onto large aircraft structures.

Relevance to Strategic Objectives

Capacity (3): Novel coatings might reduce drag, which could increase speed and deicing or self-cleaning capabilities, which would, in turn, increase operating flexibility. In addition, these coatings might enable new aircraft concepts.

Safety and Reliability (9): Novel coatings may detect damage (e.g., color change), facilitate deicing, and protect against corrosion. In this way, they can lessen the risk of catastrophic malfunction, aircraft loss, and human injury.

Efficiency and Performance (3): These coatings can reduce drag, and they offer biomimetic functionalities that may enable new aircraft capabilities.

Energy and the Environment (3): These coatings could provide environmental protection, lead to noise reduction, and be used for harvesting energy. New corrosion-resistant coatings could replace the environmentally hazardous chromium and cadmium that is currently used.

Synergies with National and Homeland Security (1): Although the DoD sponsors similar research, civil aeronautic applications would have a different emphasis, and NASA's research would not be applicable.

Support to Space (1): This Challenge has little impact on this Objective.

Why NASA?

Supporting Infrastructure (3): NASA has infrastructure relevant to this Challenge but little ongoing research.

Mission Alignment (9): This Challenge is very relevant to NASA's mission of improving aircraft capabilities.

Lack of Alternative Sponsors (3): Novel coatings are currently being explored by industry, and there is some interest in this area from DoD, but neither places sufficient emphasis on civil aeronautics applications.

Appropriate Level of Risk (9): Basic research is being done at universities. High-risk research is necessary to mature and transition this research to aeronautic applications.

C12 Innovations in structural joining

Load transfer in airframe structures is accomplished by joining discrete structural members. These joints add significant weight to the airframe, thereby reducing its efficiency. The broad classes of joining in airframe structure are mechanical fastening, adhesive bonding, and welding (for metallic structures). Significant advances have been made over the past decades in semiempirical analysis and design methods for structural joints. However, to make substantial progress, such as a 50 percent reduction in structural weight fraction, and to enable the widespread use of new joining methods, an initiative to develop a rigorous, all-encompassing simulation of performance is needed.

Joints in airframe structures are weight and cost drivers that often call for specialized treatments at the edges being joined. Improved joining technology promises significant payoffs in structural efficiency. Leakproof joints will eliminate parasitic seals in structures that must hold fluids. Efficient joints will improve airframe repairability and arrest damage propagation.

Several NASA and DoD programs have yielded test data and semiempirical models to analyze and design mechanically fastened and adhesively bonded joints. Welding of metallic structures is a well-defined and -characterized process. With the advent of ultralightweight structures using foam or honeycomb core sandwich panels, however, new mechanical fastening concepts with accompanying analysis methods are required. Friction stir welding of aluminum-lithium (Al-Li) structures needs to be modeled and a methodology for simulating complex structural arrangements needs to be developed. For adhesively bonded joints, surface preparation techniques and damage propagation arrest features need to be developed to ensure flight safety.

Currently, a rational methodology is required for adhesive surface preparation to ensure consistent, high-strength, certifiably bonded joints. A design and analysis methodology is needed for mechanically fastened joints in extreme environments along with substantiating test data. A fatigue performance and design methodology to resist cracking is required for friction stir welded joints in airframe-grade materials. Reliable, nondestructive inspection and evaluation methods are required for adhesively bonded joints. Some key milestones in advancing this technology include

- Develop certification methodology and tools for bonded joints.
- Fully characterize friction stir welding processes for Al-Li structural materials.
- Develop nondestructive strength assessment techniques for bonded joints.
- Develop modeling and simulation capabilities for mechanically fastened joints in extreme environments.

Relevance to Strategic Objectives

Capacity (3): Although this Challenge would have few direct effects on capacity, advanced joining technology is an enabler for new aircraft concepts, increased aircraft size, and increased operating flexibility.

Safety and Reliability (3): The ability to rigorously model, simulate, test, and verify joint concept performance translates directly into increased reliability and, hence, safety. This is especially significant for pressurized airframe structures.

Efficiency and Performance (9): Improvement in joint efficiency will increase structural efficiency and, thereby, aircraft efficiency and performance.

Energy and the Environment (1): Joining would only have a small, indirect impact on this Objective via improved structural efficiency.

Synergies with National and Homeland Security (3): This Challenge might have some impact on military aircraft.

Support to Space (3): This Challenge might have some impact on access-to-space vehicles.

Why NASA?

Supporting Infrastructure (3): NASA Langley has some skills left over in this area, which it developed in the early 1980s in its Aircraft Energy Efficiency Program.

Mission Alignment (9): This technology is well aligned with NASA's goals for improving airframe structural efficiency.

Lack of Alternative Sponsors (3): DoD organizations support the goals of this Challenge, although in recent years DoD has not supported relevant research.

Appropriate Level of Risk (9): Previous research addressing the very difficult task of modeling real airframe joint behavior has reduced risk to the point where this Challenge faces moderate to high risk.

C13 Advanced airframe alloys

Significant portions of aircraft structures will continue to be designed using metallic materials. New alloys that possess higher strength, inherently high fracture toughness, very high resistance to fatigue crack growth, and significantly improved corrosion resistance will enable much lighter, more efficient airframe structures with increased durability and reliability. It is important that these materials be developed along with the manufacturing science required to turn them into viable structural elements. Improved aluminum alloys have a history of very rapid insertion into aircraft applications if they provide significant performance and cost benefits, and can be recycled at the end of the aircraft's life. New chemistries, an enhanced understanding of processing–microstructure–property relationships, and improvements in processing science are enabling the development of advanced aluminum alloys with lower density, higher strength, and greater stiffness. The entire metallurgy of titanium will be redone if meltless titanium processing is shown to be practical; progress to date is quite promising.

Materials modeling is just now becoming possible at the desktop, driven by new computational tools and ever-increasing desktop computer processing capability. The conventional approach for alloy development is highly sequential and typically occurs over a long period of time—a decade or more. Use of modern materials modeling tools would facilitate the development of advanced alloys, reducing time and effort by 50 percent or more. Applying modeling to guide the advancements of these materials is in the very early stages, and NASA has the opportunity to be the leader in this technology.

The ability to model complex phase fields, microstructures, and materials processing and to estimate the full gamut of materials properties will allow many alloy trials to be conducted by computer analysis. This model-based approach for designing materials will focus limited resources on the most promising new alloy candidates. Improved materials performance directly translates into higher structural efficiency and reduced product weight; reductions of up to 25 percent appear possible. Improved modeling could increase material reliability as well.

A key focus of this Challenge is developing an integrated set of physics-based models that accurately estimate material properties of new alloys, significantly accelerating the R&D of new aerostructural metals. This effort would include the generation of fundamental data, complemented by testing that simulates realistic jet engine operating conditions to validate the model.

Industry has recently made significant improvements in conventional aluminum alloys by incrementally improving chemistry and microstructural control. For example, alloy 2025-T3 has 15-20 percent better fracture toughness and twice the fatigue crack growth resistance of 2024-T3. New Al-Li alloys have lower density and higher fatigue resistance. For example, the Al-Li alloy 2097 that replaced 2124 in an F-16 bulkhead has three times better spectrum fatigue behavior, which allows approximately 5 percent higher spectrum fatigue stress. Materials modeling could leverage the results of this latest work.

In addition, the aluminum–magnesium–scandium family offers potential for high strength and outstanding corrosion resistance. Serious consideration of these alloys has been impeded by the high cost of scandium. However, a significant reduction in the price of scandium is anticipated because a very large new ore deposit and a new refining method are coming on line in Australia.

Other alloys under development are moderate-temperature, age-hardenable aluminum alloys that could retain their strength at operating temperatures up to 150°C and would therefore be useful for a Mach 2.4 aircraft. Laminated hybrids of aluminum sheet with fiber reinforcements have high fatigue resistance and the potential for significant weight saving. The prospect of innovative chemistries that cannot be produced by conventional melting routes offers exciting new titanium materials. Meltless titanium processing has recently been demonstrated using several different processes, spurred by a current DARPA program. Advanced titanium alloys can exploit the meltless processing approach to enable very fine-grained structure with superb fatigue strength. Key milestones include

- Develop databases of the physical and mechanical properties needed for design of materials.
- Develop physics-based models that accurately estimate the properties of new alloys.
- Validate material models through alloy trials and material testing.
- Optimize new metal-processing techniques and scale them up to production size.
- Characterize new alloy families based on new alloying elements.
- Optimize and scale up processing techniques for the most promising new alloys.

Relevance to Strategic Objectives

Capacity (9): Lighter weight structures made from improved metallic structural materials will allow higher payload fractions, increasing the amount of cargo or passengers an aircraft can carry. Improved corrosion resistance and damage tolerance will reduce the time required for maintenance, improving 24/7 operational flexibility.

Safety and Reliability (1): Although these new structural alloys could provide improved reliability by enhancing corrosion resistance, fatigue strength, and inherent toughness, the focus of this Challenge will be on improved performance and efficiency rather than safety and reliability.

Efficiency and Performance (9): Better corrosion resistance directly translates into reduced maintenance and inspection costs. Better fatigue resistance will give the airframe longer life, lowering operating cost. Supersonic airplanes will greatly benefit from having affordable aluminum and titanium alloys as design alternatives to composites.

Energy and the Environment (1): This Challenge is not relevant to this Objective.

Synergies with National and Homeland Security (3): The DoD would consider using advanced airframe alloys for a variety of aeronautical systems applications, including supersonic aircraft. The range of DoD applications for advanced titanium alloys based on meltless processing would be considerable and would go beyond aeronautics. Supersonic airframes would also directly benefit from this technology.

Support to Space (1): Although these new structural materials might be considered for structural applications in access-to-space vehicles and satellite structures, these applications would require considerable additional effort for evaluation, first, and then for the development of specialized manufacturing methods.

Why NASA?

Supporting Infrastructure (1): Within NASA, the core metallurgical expertise has not been refreshed as people left the organization and the emphasis shifted to composite airframe structural materials. Airframe alloy research can leverage the thermal structures research facility at Langley and the hypersonic materials environmental test facilities at Langley, Johnson, and Ames for evaluation of the higher temperature alloys.

Mission Alignment (3): Although NASA has contributed significantly to this field, it has since been adopted by industry, and the research is less aligned with NASA's mission.

Lack of Alternative Sponsors (1): If this work were not undertaken by NASA, it would be done by industry and by DoD. The former is already leading the development of new chemistries and processing for advanced airframe alloys.

Appropriate Level of Risk (9): This Challenge faces high risk.

C14 Next-generation nondestructive evaluation

NDE is an interdisciplinary field that is concerned with the development of analysis techniques and measurement technologies for the quantitative characterization of materials and structures by noninvasive means. Ultrasonic, radiographic, thermographic, electromagnetic, and optical methods are employed to probe interior microstructure and characterize subsurface features. Currently available NDE instruments are compact, rugged, and can acquire large amounts of wide-area multiphysics data via sensor arrays. Recent better-than-Moore's-law increases in computational hardware capabilities allow these data sets to be processed with compact, rugged, and inexpensive computers. To advance NDE capabilities beyond the paradigm of rendering high-quality imagery for humans to interpret, the missing piece, more and more often, is the understanding necessary to create multiphysics algorithms that would allow the enormously rich data sets to be automatically interpreted.

The primary goal of next-generation NDE is, therefore, to develop this enabling understanding and algorithms. In the short term, the goal is to create artificial intelligence that can provide a backup assessment, as is now done in x-ray mammography. In the medium term, the primary task of NDE technicians will be to transport and set up instruments; NDE measurements and interpretation will be fully automatic. In the long term, the instrumentation could be robotic, so that NDE inspections as well as interpretation would be automated.

Next-generation NDE improves safety and reliability by minimizing manufacturing defects and identifying in-service flaws before they cause malfunctions. It enables 24/7 operation by minimizing downtime due to faults and has the potential to make just-in-time maintenance feasible. Most next-generation NDE technologies will find application in DoD and access-to-space vehicles, as well as in a variety of important nonaerospace industries. Next-generation NDE is synergistic and closely allied with IVHM research; NDE would provide inputs to prognosis and life-prediction systems.

The hardware that acquires the NDE data is becoming less and less interesting from a scientific perspective, and it is not the appropriate focus for NASA. At the same time, brute force computer image processing, rendering, and visualization is not the focus either. The human visual system is set up to deal with surfaces, not volumes of data, so it can be argued that existing NDE systems already generate data and imagery in quantities that strain or exceed human limits. Accordingly, current work is directed at bringing an understanding of the instrumentation and measurement together with sophisticated, multiphysics models of the probing energy–material interaction that is taking place.

NDE for complex materials and structures includes developing and fusing multiple sensor techniques that provide orthogonal information on the state of a material or structure, as well as improving data reduction techniques for quantitatively mapping measurements to accurately characterize material and structural integrity. Computational NDE involves developing and validating accurate multiphysics simulations to reduce the cost of optimization and automation of NDE techniques. Autonomous NDE involves the development of techniques that accurately characterize materials and structures (including damage) with minimal or no human interaction, including techniques that are self-calibrating and methodologies for assuring proper instrument setup. Key milestones include

- Demonstrate successful, real-time, fully automatic interpretation for various individual NDE techniques in targeted families of applications in the laboratory.
- Fuse multiple orthogonal NDE techniques.
- Adapt laboratory-tested NDE techniques to field-portable configurations that can be demonstrated outside of the laboratory.
- Implement large-area, multiphysics NDE techniques and instrumentation robotically.
- Transfer techniques and algorithms to IVHM efforts, including optimization of the output of next-generation NDE technologies for input to research on prognosis and life prediction.

Relevance to Strategic Objectives

Capacity (3): Current NDE relates directly to enabling 24/7 operation by reducing downtime due to faults. Next-generation NDE will be faster and more automated, and it will help to enable just-in-time maintenance.

Safety and Reliability (9): NDE directly supports safety and reliability by minimizing manufacturing defects and identifying in-service flaws before they cause a malfunction. Next-generation NDE is synergistic and closely allied with IVHM efforts and provides input to prognosis and life-prediction systems.

Efficiency and Performance (1): Although next-generation NDE imparts enough confidence to permit adopting new material systems and structural concepts as well as to operate safely closer to performance margins, the improvement over current NDE will have less of an impact on this Objective than other technologies.

Energy and the Environment (1): This Challenge is not relevant to this Objective.

Synergies with National and Homeland Security (3): Some NDE technologies are applicable to security screening areas, in particular the automated real-time interpretation of multiphysics measurements. Most next-generation NDE technologies will also find application in DoD aircraft and other vehicles, with moderate impact expected.

Support to Space (1): Most next-generation NDE technologies will find some application in access-to-space vehicles, but the impact will be minimal because the small number of reusable vehicles means that most NDE applications for space will be for manufacturing quality control and related issues prior to flight.

Why NASA?

Supporting Infrastructure (3): NDE equipment and research facilities tend to be compact, relatively inexpensive, and broadly available, but NASA has some staff with unique expertise.

Mission Alignment (9): This Challenge is very relevant to NASA's mission in terms of (1) aviation safety (especially aging aircraft) and (2) facilitating development and insertion of new materials, structures, and processes by ensuring that they are manufactured according to specifications and are behaving as designed as they are put into service.

Lack of Alternative Sponsors (1): DoD and nonaerospace industries are supporting NDE research. Focusing on automated interpretation of multiphysics NDE measurement data would provide a niche where NASA could collaborate with academia without duplicating work by others.

Appropriate Level of Risk (3): Given that this Challenge encompasses many tasks that are standard industrial practice now, it faces low risk.

C15 Aircraft hardening

Improved aviation security requires that commercial aircraft be hardened against safety threats such as explosions and biological or chemical agents. Effective solutions will encompass detection, avoidance, and impact minimization of threats. The large number of potential threats and path-ways for delivery dictates the development of multiple and varied technologies, ranging from sensors for threat identification and structural health monitoring to the development of highly durable blast containment systems and methods to accurately model structural damage due to blast events. Successfully hardening commercial aircraft increases their safety and reliability and contributes to on-ground safety by minimizing the use of aircraft as weapons.

Biological and chemical threat detection sensors and self-decontaminating coatings are in the early development stages. Hardening technologies developed for military aircraft such as fuel inerting and nonreflective, infrared-absorbing paint for signature reduction remain largely unimplemented for commercial flight because of their weight and/or cost. These considerations have also limited the use of blast containment technologies in commercial aircraft even though there has been a significant effort by the FAA and commercial companies to develop blast-resistant luggage containers, also known as hardened unit-loading devices.

Various schemes for improving the energy absorption capacity of the luggage containers have been investigated, including incorporation of honeycomb or foam elements. In addition, instead of using aluminum or fiberglass as the primary structural material, new containers could use (1) composites reinforced with fibers developed specifically for ballistic armor applications (e.g., Kevlar, Spectra, and Zylon) or (2) hybrid systems (e.g., a laminate composed of fiberglass and aluminum foil). FAA-certified designs have been developed and verified through blast testing. Inspection, maintenance, and repair methodologies, however, have not been adequately addressed. Similar concepts are currently under development for hardening overhead bin compartments.

Many of the impediments to incorporating threat-hardening technology in commercial aircraft stem from the constraints imposed by retrofitting existing aircraft and the difficulty of analyzing rapidly loaded, complex structures. The cost and weight of hardening existing aircraft is prohibitive. New aircraft designs will more efficiently incorporate features such as fuel protection filters; integrated threat detection (including biometric identification); health monitoring sensors; and highly durable, fire-resistant composite structures. Key milestones include

- Analyze, design, and test an optimized blast-resistant luggage container.
- Develop and validate accurate damage prediction models for blast events including shock overpressure and crack propagation due to hull pressurization.
- Integrate onboard biological and chemical sensors.
- Model and develop self-decontaminating coatings.

Relevance to Strategic Objectives

Capacity (1): Hardening of aircraft can reduce vehicle losses, but the weight increase associated with blast hardening in particular would decrease capacity.

Safety and Reliability (9): Hardening is a key strategy for improving aircraft safety by providing protection from onboard explosions and improving threat assessment.

Efficiency and Performance (1): Hardening would likely have a nominal or negative impact on this Objective due to increased weight.

Energy and the Environment (1): Hardening would likely increase structural weight and possibly volume, which could indirectly increase noise and emissions.

Synergies with National and Homeland Security (9): This Challenge is very relevant to DHS and DoD missions.

Support to Space (1): This Challenge has no impact on this Objective.

Why NASA?

Supporting Infrastructure (3): NASA supported relevant research under its Aviation Safety and Security Program, where the topics included control systems to detect and compensate for vehicle damage; fuel protection; fire-resistant, damage-tolerant composites; and sensing of onboard chemical and biological contamination.

Mission Alignment (3): Although NASA's 2003 Strategic Plan specifically discusses the need for NASA to "aggressively apply our expertise and technologies to improve homeland security," this Challenge is more closely related to the mission of DHS.

Lack of Alternative Sponsors (1): The FAA, DHS, DoD, and industry are all sponsoring research for hardening technology.

Appropriate Level of Risk (9): This Challenge faces moderate to high risk.

C16 Multiphysics and multiscale modeling and simulation

Multiscale and multiphysics modeling and simulation encompass computational modeling of interdisciplinary systems at multiple spatial and temporal scales (e.g., by finite-element methods, molecular dynamics, and ab initio methods). With advances in the understanding of material and system behavior at multiple spatial scales (from atomistic to continuum) and time scales (from the period of atomic vibration to structural lifetime) when subjected to multiple physical stimuli (mechanical, thermal, electromagnetic, chemical), the promise of designing new materials based on atomic characteristics is emerging. Given a specific requirement (e.g., strength, stiffness, or piezoelectric coefficient), it may become possible to design a new material from the atomic level up that will meet the requirement, replacing the make-it-and-break-it approach currently used to investigate new material systems.

Multiscale and multiphysics modeling has been examined for several years, but is still in its infancy. With recent advances in computational capabilities, there has been renewed interest in multiscale and multiphysics modeling. DoD has invested in this field through various programs, including the Multidisciplinary University Research Initiatives (MURIs), Materials Engineering for Affordable New Systems (MEANS) grants, and DARPA programs. Multiscale, multiphysics modeling has been identified as an integral component of the National Nanotechnology Initiative, which promises to invest close to $1 trillion per year in product development over the next 10 years. A number of leading universities are also beginning work in this area.

From a programmatic viewpoint, the research problems are inherently twofold. Overcoming this Challenge requires researchers familiar with multiple physical phenomona (mechanical, thermal, electromagnetic, chemical). In addition, it requires facilities with high-end computer facilities for storing, processing, and managing large data sets. Substantial computer power is required to construct even small-scale simulations of materials. Complex systems require tens to hundreds of simulations, requiring high-performance computing support (in general, hundreds to thousands of processors) to complete the simulations in a reasonable time frame. Similarly, each simulation can generate terabytes to petabytes of data. Thus, state-of-the-art visualization, data mining, and data analysis techniques are also critical to the success of this Challenge. Key milestones include

- Select an aeronautics-related material test problem.
- Develop multiscale, multiphysics modeling software representative of the selected test problem.
- Procure necessary computer facilities for the modeling effort.
- Measure critical parameters necessary for formulating the models, including measurements made using electron-based optics with the ability to perform energy dispersive spectroscopy or electron energy loss spectroscopy.
- Complete a multiscale, multiphysics analysis of the selected test problem.
- Validate modeling by comparing the results to those of an experimental development program.

Relevance to Strategic Objectives

Capacity (3): Multiscale and multiphysics modeling will enable the development of revolutionary new material systems. These new materials will be lighter, stiffer, and stronger than current material systems, leading to increased payload fractions, so that an aircraft of given size will be able to carry more passengers or cargo.

Safety and Reliability (3): Multiscale and multiphysics modeling will allow a complete understanding of the manner in which materials fail. This will improve safety and reliability by improving the ability to predict and account for structural failures.

Efficiency and Performance (3): Multiscale and multiphysics modeling will lead to new, possibly more efficient materials for aircraft propulsion systems.

Energy and the Environment (3): Multiscale and multiphysics modeling will improve the understanding of acoustic dampening properties and interactions between airflow and structures. These improvements will aide in the development of quieter aircraft.

Synergies with National and Homeland Security (3): Multiscale and multiphysics modeling is going on throughout DoD—for example, to create new materials that are immune to radiation effects for use in nuclear reactors. Nationally, much of the research relevant to this Challenge (including DoD-funded research) is conducted by universities, and it is still at a low level of technology readiness. Therefore, the impact on national security, at least in the near term, will be limited.

Support to Space (1): Multiscale and multiphysics models applicable to civil aeronautics focus primarily on interactions between mechanical, material, and flow phenomena. Since high temperatures typical of space reentry vehicles are a minor consideration, most of the research relevant to this Challenge would not be applicable to space applications.

Why NASA?

Supporting Infrastructure (3): Facilities and personnel at NASA's Langley and Glenn Research Centers are supporting research relevant to this Challenge. Superior facilities and personnel may exist at many universities, however.

Mission Alignment (3): This Challenge is relevant to NASA's mission. However, the technology is in the early stages of development, and current research is rather generic. As these materials are advanced to the point where specialized research with a focus in aeronautical applications becomes necessary, the Challenge will become more relevant to NASA's mission.

Lack of Alternative Sponsors (3): DoD, DOE, and some universities are conducting research relevant to this Challenge. However, without NASA's attention, this research may never be used to develop materials and structure necessary for civilian aeronautical applications. Additionally, NASA's expertise in multidisciplinary design and optimization means that NASA is well qualified to implement much of the work done elsewhere.

Appropriate Level of Risk (3): Relevant technology is currently at a very early stage of development; this Challenge faces very high risk.

C17 Ultralight structures

The current state of the art in lightweight airframe structures is demonstrated by the Boeing 787, which makes extensive use of structural composites. Lightweight structures enable aircraft with longer range, more fuel efficiency, greater payload, and/or lower operating costs. Ultralightweight airframe designs would increase these payoffs.

Ultralight structures programs have been characterized by highly innovative concepts that test the boundaries of the possible. The Gossamer Condor demonstrated human-powered flight. Several NASA and DoD ultralight airframe programs have produced prototype high-altitude, long-endurance UAVs, such as Helios, which demonstrated solar-powered flight. Typically these ultralightweight aircraft have been point-designed for specific flight conditions. To achieve their objectives, they disregarded usual aircraft design practices such as minimum skin thicknesses, redundant load paths, and damage-tolerant design criteria. The designs demonstrated in these programs are not robust enough to meet the strict certification requirements for commercial aircraft. However, they do motivate pragmatic adaptations of ultralightweight structural concepts suitable for commercial application. Promising concepts for ultralight airframes include the use of foam or honeycomb core-stiffened structures with integral, durable damage arrest features; high-performance fibers for increased strength; directional tailoring and unitized construction; and structural optimization methods. Including adaptive materials for variable camber morphing wings may reduce control surface weight. Embedding multifunctional technologies, such as integral antennas or new flexible polymer solar cells, could reduce subsystem weights. The details of many of these concepts have been discussed in other, more highly ranked R&T Challenges. A new initiative is needed to integrate these concepts and the associated design and analysis technologies, along with the substantiating test data, to enable robust, ultralightweight airframe structures for commercial transport applications. Key milestones include

- Develop specific ultralightweight airframe concepts, leveraging lessons learned from experimental ultralight aircraft research to develop damage-tolerant, adaptive, and multifunctional materials.
- Develop a design and analysis methodology.
- Develop a structural optimization methodology.
- Perform verification testing.
- Demonstrate the potential of one or more concepts to reduce airframe weight by 40 percent.

Relevance to Strategic Objectives

Capacity (3): Reducing airframe weight can increase payload fraction, meaning that an aircraft of a given size will be able to carry more passengers or cargo. Ultralight airframes may enable new aircraft concepts and increased operating flexibility.

Safety and Reliability (1): This Challenge is not relevant to this objective.

Efficiency and Performance (3): Reducing airframe weight will help reduce aircraft operating costs and increase structural efficiency and performance.

Energy and the Environment (1): This Challenge would only have a small, indirect impact on this Objective via improved structural efficiency.

Synergies with National and Homeland Security (3): Some aspects of this technology, such as structures for micro-UAVs and long-endurance surveillance aircraft, are of great interest to the DoD and DHS.

Support to Space (3): This Challenge is relevant to the design of space structures.

Why NASA?

Supporting Infrastructure (3): NASA Langley has some relevant skills left over from the Advanced Composites Technology Program of the 1980s.

Mission Alignment (9): This Challenge is well-aligned with NASA's improved airframe efficiency goals.

Lack of Alternative Sponsors (1): DoD organizations support this goal, although in recent years there has been no investment in this area. Private entrepreneurs' investment in innovative ultralightweight concepts is frequently motivated by setting new aviation performance records (speed, altitude, endurance, etc.).

Appropriate Level of Risk (3): Incremental research to reduce the weight of airframe structures has been under way for a long time. Therefore, this Challenge faces low risk.

C18 Advanced functional polymers

Polymers that adapt their properties or alter their form in response to a change in their environment are known as functional or stimuli-responsive materials. Polymeric materials have demonstrated many responses coupled to a wide range of stimuli (temperature, pH, ionic strength, electrical potentials, and light). These polymers can provide unique functionality of great benefit to aeronautical and aerospace applications. They hold particular potential for achieving biomimetic functionality and sensing.

Potential benefits from this broad-based technology include new sensing capabilities, self-healing polymers for passive repair of damage, reversible liquid crystal adhesives, phase changing polymeric materials for managing interior temperatures, superabsorbent polymers for fire retardation, nanocomposite dispersions providing longer life and resistance to dirt (e.g., self-cleaning), ionic polymers for actuation, color change or other reaction to stress or an environmental threat, conductive polymers, and materials with energy-harvesting capabilities. Development of advanced functional polymers is an active research area in both academia and industry. However, many current applications are not necessarily targeted for aeronautics or aerospace. Many potential functionalities (e.g., self-healing and self-cleaning) have been demonstrated in the laboratory environment, but only in small samples have been generated. Field testing remains to be done. There is also a need to improve the durability and environmental stability of these materials so they can survive at very high or very low temperatures and in corrosive conditions. It would also be helpful to reduce the need for expensive catalysts or other additives, which many advanced functional polymers require.

Functional polymers are an emerging field with significant opportunity for synthesis and characterization of new polymers to achieve the varied applications described above. Key milestones include

- Demonstrate cost-effective methods for processing larger quantities of functional polymers.
- Transition new functional polymers from research laboratories to the sizes needed for aircraft component testing.
- Develop more robust, environmentally stable formulations that can survive in aircraft environments.

Relevance to Strategic Objectives

Capacity (1): Advanced functional polymers may increase operating flexibility, but the impact on aircraft size, new vehicle concepts, and speed will not be significant.

Safety and Reliability (3): Advanced functional polymers can enable self-repair, improve damage detection and fire retardation, and simplify maintenance.

Efficiency and Performance (1): This Challenge has no impact on this Objective.

Energy and the Environment (1): Advanced functional polymers may provide some energy-harvesting capabilities, but the impact on noise, emissions, environmental hazards, and development of alternative fuels is minimal.

Synergies with National and Homeland Security (3): Chameleon-like functionality, self-assessment, self-repair, and autonomous functions are of interest to DoD and DHS, which also fund research relevant to this Challenge.

Support to Space (1): This Challenge has no impact on this Objective.

Why NASA?

Supporting Infrastructure (9): NASA Langley Research Center has unique, relevant infrastructure for polymer research.

Mission Alignment (3): Development of functional polymers for aeronautics and aerospace applications is aligned with the NASA mission of increasing aircraft performance. However, the technology is in the early stages of development and current research is rather generic. As these materials are advanced to the point where specialized research with a focus in aeronautical applications becomes necessary, the Challenge will move into closer alignment with NASA's mission.

Lack of Alternative Sponsors (3): DoD sponsors work in this broad area, but the focus is on military applications.

Appropriate Level of Risk (3): At this stage, with basic research mainly done at universities, this Challenge faces low risk. However, when the technology advances to the point where research results are ready to be transitioned to aeronautical applications, the risk will increase.

C19 Advanced engine nacelle structures

Engine nacelles and pylons are critical portions of aircraft structure. Nacelles enclose the jet engine and pylons provide means for mounting the engine on the airframe. The front portion of a nacelle also directs air into the engine inlet and thus affects performance of the engine. For large commercial airplanes, nacelle designs have not appreciably advanced for a generation. Consequently, nacelle structures have not taken advantage of recent developments in materials and structures technology. The result is nacelles that weigh more than they should, which decreases range, payload, and airframe fatigue life.

New structural concepts take advantage of modern analytic design tools and advanced structural materials to significantly reduce the weight while maintaining structural integrity and improving engine efficiency.

Nacelles and pylons are critical structures that affect airworthiness, so that any change from current practice must be well understood, analyzed, and validated to assure that it gives at least the same level of safety as existing structures, which have served well in many airplane applications. Key milestones include

- Define the attributes of new design concepts for nacelles that reduce weight and engine noise based on input from large and small aircraft manufacturers as well as NASA experts.
- Perform multidisciplinary design analysis to identify new structural concepts for both large and small airplanes.
- Validate the analysis via testing of subscale models of these new concepts.
- Test design at full scale.

Relevance to Strategic Objectives

Capacity (3): Lighter weight nacelles would allow a higher payload fraction, meaning that an aircraft of a given size would be able to carry more passengers or cargo. However, this particular Challenge may have more overall benefit for small airplanes than for large ones.

Safety and Reliability (1): This Challenge would ensure that pylons and nacelles are as safe and reliable as current systems, but there would be no net improvement for aircraft or the airspace system as a whole.

Efficiency and Performance (3): This technology will leverage advanced analytic tools and advanced structural materials to significantly reduce the weight of these structures. As with capacity, effects may be more pronounced for smaller aircraft.

Energy and the Environment (1): This Challenge would offer little reduction in community noise.

Synergies with National and Homeland Security (1): DoD may gain the advantage of this technology once it becomes standard practice in the aeronautical industry. However, it is not likely to be active in advancing this Challenge. Furthermore, as noted before, larger aircraft, such as the tankers and transports the DoD would be interested in, would benefit less.

Support to Space (1): This Challenge has no impact on this Objective.

Why NASA?

Supporting Infrastructure (1): NASA seems to have little or no infrastructure relevant to this Challenge.

Mission Alignment (9): This Challenge is very relevant to NASA's mission to improve aircraft performance.

Lack of Alternative Sponsors (1): Although there is currently no known effort within government or industry, this is the sort of research that should be pursued by original equipment manufacturers. If they feel the payoff is great enough, they will pursue the technology themselves.

Appropriate Level of Risk (3): Although there is currently no known effort within government or industry, this is the sort of research that manufacturers should support. There, too, if they conclude the payoff is high enough, they will pursue the technology themselves.

C20 Repairability of structures

Modern airframes, whether composite or metallic, require repairs either to restore functionality or to extend their lives. To assess the repairability of structures and make correct repair-or-replace decisions, structural assessment methods and tools, tools for trade-off analyses, and repair technologies and processes are required. These methods, technologies, tools, processes, and analyses must be applicable to metallic, polymer composite, and ceramic composite structural elements.

The primary benefit of being able to assess repairability and repair airframe parts instead of replacing them is lower direct operating costs. Life extension via repair of aging aircraft also has a significant economic impact in the form of lower acquisition costs.

Several NASA and DoD programs and manufacturers' repair manuals for aircraft owners and operators provide up-to-date tools and processes for making airframe repairs. The DoD has published a repair design guide for combat and transport aircraft. However, new algorithms are needed that incorporate validated analysis of crack growth criticality in metals, defect or damage propagation in composites, and mathematical models for stress corrosion cracking. Further, these algorithms need to be integrated with repair integrity evaluation analyses to provide a complete modeling and simulation capability that assesses the economic effectiveness of the repair method.

Fatigue and fracture analysis and databases for metals and composites used in airframe construction need to be developed, along with software enabling complete modeling and simulation of repairs, including cost considerations, to identify realistic trade-off alternatives. Key milestones include

- Conduct damage and damage growth analyses for metallic and composite structures.
- Collect a compendium of repair processes for metallic and composite structures.
- Demonstrate computer codes to model and simulate repairs for decision making.

Relevance to Strategic Objectives

Capacity (3): Effective airframe repairs will increase operating aircraft availability.

Safety and Reliability (3): Improved quality of airframe structure repairs will reduce the likelihood of loss or human injury.

Efficiency and Performance (3): This Challenge reduces aircraft operating costs and postpones the need for new aircraft purchases.

Energy and the Environment (1): This Challenge would only have a small, indirect impact on this Objective by extending structural life.

Synergies with National and Homeland Security (1): The focus of this Challenge would be on the needs of civil aircraft.

Support to Space (1): This Challenge focuses on repairability issues for air-breathing aircraft and would likely have little relevance for access-to-space vehicles, which operate in extreme environments.

Why NASA?

Supporting Infrastructure (3): NASA Langley has some capability relevant to this Challenge as a legacy of several fatigue and damage propagation research programs related to metallic and composite airframe structures during the 1970s and 1980s. These skills would need to be augmented and updated.

Mission Alignment (3): This Challenge is aligned with NASA's mission to improve aeronautical technology, but it addresses issues with operational aircraft that are also industry's responsibility.

Lack of Alternative Sponsors (1): This technology should be undertaken by industry; in the past, DoD has supported this goal as well.

Appropriate Level of Risk (3): This Challenge faces low to moderate risk.

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D

R&T Challenges for Dynamics, Navigation, and Control, and Avionics

A total of 14 R&T Challenges were prioritized in the guidance, navigation, and control, and avionics Area. Table D-1 shows the results. The R&T Challenges are listed in order of NASA priority. National priority scores are also shown.[1] This appendix contains a description of each R&T Challenge, including milestones and an item-by-item justification for each score that appears in Table D-1.[2]

D1 Advanced guidance systems

Advanced guidance systems consist of subsystems and processes (hardware and software) assembled for the purpose of providing an aircraft, spacecraft, or other dynamic system with desired state trajectories. These trajectories can be defined using either discrete or continuous data and can include information such as current velocity, acceleration, time of arrival, and desired position. The determination of the desired trajectory usually takes into account mission-dependent constraints, which can include obstacles (such as terrain, wake vortices, or other aircraft), hazards (such as weather), coordination with other aircraft (such as cooperative and multiaircraft guidance, formation flight, or swarming), and regulatory constraints (such as airspace class restrictions) (Doebbler et al., 2005).

State-of-the-art guidance systems enable aircraft to follow waypoints, perform automatic obstacle avoidance, and fly in formation with other aircraft (Schierman et al., 2004). Additional research is needed to develop guidance algorithms and mature them into flight-ready systems,[3] to develop improved reconfigurable and adaptive guidance systems, and to develop advanced guidance systems for UAVs. One concern, for example, is the need to develop improved technologies to avoid controlled flight into terrain, particularly in the case of all-weather operation of advanced rotorcraft. Some important research is inhibited by the limited number of programs and facilities capable of implementing and flying these systems on real aircraft. Also, certification and regulatory issues must be resolved so that the air transportation system can take advantage of the full capabilities of current and future guidance systems for piloted aircraft and UAVs.

Advanced guidance systems have the potential to greatly improve the capacity, safety, and efficiency of the air transportation system. In addition, they can enhance the performance of many existing and future military systems. Key milestones include

- Development of advanced algorithms and avionics for collision, terrain, and wake vortex avoidance; formation flight and cooperative and multiaircraft guidance; and ground operations guidance (taxi, takeoff, rollout, and turnoff).
- Expansion of facilities and programs capable of maturing the above technologies to flight-ready systems.
- Development and adoption of regulations for the certification and operation of autonomous UAVs in civil airspace.

Relevance to Strategic Objectives

Capacity (9): Advancing the state of the art in multiaircraft and cooperative guidance will allow more aircraft per unit time to move through the available airspace.

Safety and Reliability (9): Advanced guidance systems will allow aircraft to operate more safely in closer quarters than is currently possible both in the air and on the ground.

[1] The prioritization process is described in Chapter 2.

[2] The technical descriptions for the first 10 Challenges listed below are essentially the same as the technical descriptions for these Challenges as they appear in Chapter 3.

[3] R. Duren, associate professor, Baylor University, "Avionics research challenges," Presentation to Panel D on November 15, 2005.

TABLE D-1 Prioritization of R&T Challenges for Area D: Dynamics, Navigation, and Control, and Avionics

		Strategic Objective							Why NASA?					
R&T Challenge		Capacity	Safety and Reliability	Efficiency and Performance	Energy and the Environment	Synergies with Security	Support to Space	National Priority	Supporting Infrastructure	Mission Alignment	Lack of Alternative Sponsors	Appropriate Level of Risk	Why NASA Composite Score	NASA Priority Score
	Weight	**5**		**3**		**1**			**1/4 each**					
D1	Advanced guidance systems	9	9	9	3	3	3	**132**	9	9	3	9	**7.5**	**990**
D2	Distributed decision making, decision making under uncertainty, and flight-path planning and prediction	9	9	9	3	3	3	**132**	3	9	3	9	**6.0**	**792**
D3	Aerodynamics and vehicle dynamics via closed-loop flow control	1	9	9	3	3	3	**92**	9	9	3	9	**7.5**	**690**
D4	Intelligent and adaptive flight control techniques	3	9	9	3	3	9	**108**	3	9	3	9	**6.0**	**648**
D5	Fault-tolerant and integrated vehicle health management systems	3	9	3	1	3	9	**84**	9	9	3	9	**7.5**	**630**
D6	Improved onboard weather systems and tools	9	9	3	1	1	1	**104**	9	9	3	3	**6.0**	**624**
D7	Advanced communication, navigation, and surveillance technology	9	9	9	3	3	3	**132**	3	9	3	3	**4.5**	**594**
D8	Human–machine integration	3	9	9	1	3	3	**96**	3	9	3	9	**6.0**	**576**
D9	Synthetic and enhanced vision systems	3	9	3	1	1	3	**76**	9	9	3	3	**6.0**	**456**
D10	Safe operation of unmanned air vehicles in the national airspace	3	9	3	1	9	1	**82**	3	9	3	3	**4.5**	**369**
D11	Secure network-centric avionics architectures and systems to provide low-cost, efficient, fault-tolerant, onboard communications systems for data link and data transfer	9	9	9	1	9	3	**132**	3	3	1	3	**2.5**	**330**
D12	Smaller, lighter, and less expensive avionics	1	3	9	3	3	9	**68**	3	3	3	3	**3.0**	**204**
D13	More efficient certification processes for complex systems	3	9	9	1	1	3	**94**	3	1	1	3	**2.0**	**188**
D14	Design, development, and upgrade processes for complex, software-intensive systems, including tools for design, development, and validation and verification	3	9	3	1	1	3	**76**	1	3	1	1	**1.5**	**114**

Efficiency and Performance (9): The ability to safely operate aircraft closer to each other will allow more efficient use of the airspace and airport real estate.

Energy and the Environment (3): Advanced guidance systems can enable arrival and departure trajectories that reduce community noise. Also, multiaircraft guidance systems can increase fuel efficiency.

Synergies with National and Homeland Security (3): Cooperative and autonomous capabilities are also applicable to military aircraft.

Support to Space (3): Many multiaircraft guidance algorithms are applicable to satellite constellations and formations of mini- and microsatellites.

Why NASA?

Supporting Infrastructure (9): NASA has air transportation system simulation facilities and manned and unmanned aircraft simulation and flight test facilities. In addition, NASA has also been the primary facilitator of the unique and highly relevant Access 5 program.

Mission Alignment (9): This Challenge will have a broad benefit for aeronautics in general, and NASA has often done related research.

Lack of Alternative Sponsors (3): DoD is doing some military-specific work related to this Challenge. Relevant work by industry and academia is limited by certification and regulatory issues as well as the prohibitive cost of test facilities.

Appropriate Level of Risk (9): This Challenge faces moderate to high risk.

D2 Distributed decision making, decision making under uncertainty, and flight path planning and prediction

Improving the decision-making process used by pilots and aircraft systems, when coupled with improvements in flight-path planning and prediction, has been theorized as an effective approach to improving air transportation system capacity and safety. This Challenge has the potential to significantly improve the timeliness of real-time decisions to alter flight paths in the dynamic environment of congested airspace (Ding et al., 2004; Helbing et al., forthcoming; Rong et al., 2002). Coordinated decision making, which includes the direct exchange of data among different aircraft and the deconfliction of flight paths without the need to rely on ground-based controllers, addresses the inherent limitations of centralized ATC systems in terms of uncertainty and fault tolerance. A coordinated, distributed approach to decision making increases air transportation system reliability and safety by distributing control and mission management capabilities among multiple agents. It also allows for rapid response to changing dynamics and minimizes vulnerability to system failures.

Automated systems can help improve decision making and flight path planning. Levels of automation ranging from “pilot aid” (that is, systems that advise pilots to take specific action) to “fully autonomous” are achievable but have not yet been developed to the point where they can support high levels of automation for civil aircraft. Until now, coordinated distributed algorithms for constraint reasoning (for example, to optimize flight paths) have not been applied to the air transportation system because implementation with such a complex system would require aircraft to exchange a large number of messages, which raises substantive communications, bandwidth, and man–machine interface issues.

This Challenge should address the needs of a wide variety of conventional and unconventional aircraft types, including those with no distributed decision-making capability. Aircraft types of interest include commercial airliners, general aviation aircraft, civil helicopters, military aircraft, and UAVs.

This Challenge also has the potential to be of great benefit when applied to complex, nonaviation systems that operate in dynamically changing environments and require high-quality, real-time decision making. Key milestones include

- Develop fundamental system requirements, architectures, and system logic that are compatible with current and future regulatory requirements and ATM systems. This Challenge should include studies to determine the levels of automation appropriate to a wide range of decision-making applications.
- Develop simulation capabilities for evaluation and demonstration of certain high-performing strategies in the execution of realistic system architectures and applications.
- Develop a requirements flowdown to all affected aircraft systems, such as advanced communications, navigation, and surveillance (CNS) systems.
- Develop improved, automated logic and processes for contingency management.
- Develop a methodology to support verification and validation of future systems technologies developed by this Challenge.

Relevance to Strategic Objectives

Capacity (9): The capability to accomplish dynamic real-time flight path planning and replanning in the dynamic airspace environment will allow closer separations and increase capacity.

Safety and Reliability (9): The capability to accomplish dynamic high-quality flight path planning and replanning in the dynamic airspace environment will allow closer aircraft separations with increased safety.

Efficiency and Performance (9): The capability to accomplish automated and autonomous high-quality, real-time flight path planning and replanning in the dynamic airspace environment will reduce aircrew and controller workloads as well as the demands on the entire ATM system. Training requirements will also be reduced at all levels within the system.

Energy and the Environment (3): Dynamic flight path replanning can be used to improve mission efficiency and reduce fuel burn.

Synergy with National and Homeland Security (3): The capability to accomplish dynamic, high-quality, real-time decision making (e.g., planning and replanning) will have many applications in the national and homeland security environment, including the future integration of UAVs into the air transportation system.

Support to Space (3): Coordinated distributed decision making is very beneficial for spacecraft guidance, navigation, and control (GNC) tasks such as flight planning, rendezvous and docking, and reentry.

Why NASA?

Supporting Infrastructure (3): NASA has significant facilities and some experience relevant to this Challenge.

Mission Alignment (9): This Challenge will directly support multiple R&T Challenges and benefit military and civil aviation, as well as future applications in space.

Lack of Alternative Sponsors (3): Industry is developing technology relevant to this Challenge, but it is more geared to military systems with a focus on UAVs.

Appropriate Level of Risk (9): Mid- and long-term research can address issues related to this Challenge, and the results can be transferred to future civil and military applications.

D3 Aerodynamics and vehicle dynamics via closed-loop flow control

Closed-loop flow control appears to offer tremendous promise in improving aerodynamic performance. For example, active flow control approaches should allow the airfoil lift:drag (L/D) to remain high over large changes in angle of attack.[4] Flow control R&T could also be used to develop a spoiler-aileron to replace complex and heavy control surfaces and to reduce or eliminate turbulent flow over aircraft surfaces to reduce skin-friction drag. These applications could lead to new aircraft configurations (Chavez and Schmidt, 1994).

The mechanization of flow control systems may require a large number of distributed sensors measuring pressure or shear stress over the wing and changes in the boundary layer. Actuation might be accomplished by morphing the wing or introducing devices that induce sucking or blowing along the wing. These distributed sensors and actuators are coordinated so that control is obtained over large flight regimes, angles of attack, and attitudes.

Distributed sensing and actuation would also permit structures to be self-aware for health monitoring, thereby increasing system reliability. Airframe and engine structures could be monitored for changes in behavior.

Some of the techniques developed by this Challenge may also advance modeling and design capabilities applicable to morphing aircraft (Tandale et al., 2005; Valasek et al., 2005). Heretofore, aircraft have generally been fixed-frame structures. Morphing aircraft would be designed with distributed actuation and controls and with mechanization as an inherent property. They would lead to new capabilities and concepts in aircraft design. Examples include (1) biomorphic aircraft, such as ornithopters, that could maneuver robustly in complex environments and (2) hunter-killer aircraft that change shape to optimize performance for different tasks (e.g., surveillance, reconnaissance, and ground attack). Morphing technology might also enable aircraft capable of perching. Key milestones include

- Develop simpler representations of the aircraft system dynamics for control design.
- Develop distributed control algorithms and architectures.
- Demonstrate the ability to numerically solve distributed control algorithms at the Reynolds numbers associated with manned aircraft flight to demonstrate control performance.
- Implement integrated, distributed closed-loop flow control systems.
- Design and develop lightweight, mechanized, shape-changing structures.
- Experimentally verify the performance of shape-changing aerodynamic structures before flight testing.

Relevance to Strategic Objectives

Capacity (1): This Challenge has minimal application to this Objective, although networks of sensors and actuators could be utilized to monitor and maintain fleet readiness.

Safety and Reliability (9): Large arrays of sensors and actuators vastly improve system redundancy.

Efficiency and Performance (9): Adaptable flight characteristics will improve mission performance over a variety of conditions.

Energy and the Environment (3): Extremely high L/D reduces fuel usage, and adaptable engines could significantly reduce noise and emissions.

Synergies with National and Homeland Security (3): This Challenge will facilitate the development of UAVs with long endurance for surveillance.

[4]The flow over the specially shaped GLAS II airfoil remains naturally separated at the rear of its upper surface over a wide range of angles of incidence; in the absence of active control, its L/D does not exceed 25. At an incidence angle of 10 degrees, its L/D is nearly 500 (Glauert, 1945, 1948).

Support to Space (3): This Challenge could (1) improve the performance of aerodynamic first-stage launch vehicles, which would increase payload capacity, and (2) enhance the endurance of aircraft design to fly in the martian atmosphere. Shape control also allows for safer transatmospheric flight.

Why NASA?

Supporting Infrastructure (9): NASA has been a leader in computational fluid dynamics, producing the first direct numerical computation of the Navier-Stokes equations. Furthermore, Langley Research Center and Ames Research Center have conducted flow control R&T. Finally, existing NASA wind tunnels could be important for experimental verification of flow control algorithms.

Mission Alignment (9): This Challenge is very relevant to NASA s mission.

Lack of Alternative Sponsors (3): DoD is doing a lot of research relevant to this Challenge and has coupled it with funding to many universities.

Appropriate Level of Risk (9): This Challenge faces moderate to high risk.

D4 Intelligent and adaptive flight control techniques

The missions and capabilities of future aircraft, both manned and unmanned, will be more multifunctional than those of the current generation of specialized aircraft. Achieving aggressive performance targets in range, payload, reliability, safety, noise, and emissions will require a total system that is integrated to a far higher level than existing aircraft. R&D for military aircraft has been able to push the technological envelope associated with intelligent and adaptive flight control techniques farther than R&D for civil aircraft because of different safety limits. In the far term, as it advances, application of military technology to civil aircraft may be possible.

The vehicle management systems (VMS) paradigm offers the most promising path to realizing goals related to this Challenge. VMS takes a top-down systems approach to specifying, designing, and validating the aircraft as a single system with highly integrated inner and outer loops. It thereby unifies the traditionally separate fields of propulsion control, flight control, structural control, noise control, emissions control, and health monitoring. The current state of the art in VMS uses traditional feedback control, consisting of measurements of vehicle states such as airspeed, altitude, angle of attack, and linear and angular acceleration (Jaw and Garg, 2005). By incorporating an online learning capability to cope with new and unforeseen events and situations and nonlinear adaptive control, in which the controller self-tunes to maintain stability and tracking in the presence of disturbances and changing vehicle parameters, an intelligent and adaptive VMS can be developed with the promise of significant advances in capability, safety, and supportability (Tandale and Valasek, 2003).

Significant advances in the state of the art are required to develop an intelligent and adaptive VMS. Current nonlinear adaptive control approaches assume that (1) sensor information is reliable and (2) known nonlinearities can be modeled as slowly varying parameters that affect the system linearly. However, advanced actuators for flow control and structural control will have characteristics that are much more nonlinear than those of conventional control actuators. Control laws and control actuator allocation are currently treated as separate problems, such that optimization of the integrated control law is difficult or impossible. Finally, the problem of multiple correlated, simultaneous failures remains unsolved. Approaches that use analytic redundancy to finding failed sensors generally assume that aircraft dynamics have not changed, while adaptive or reconfigurable control approaches assume that sensor information is reliable. On an affordable aircraft with limited or no sensor redundancy, it is difficult or impossible to tell the difference between a degraded sensor and damage to the aircraft that changes the way it flies. Key milestones include

- Develop an adaptive, intelligent, fully integrated VMS that can operate safely without reliable sensor information.
- Demonstrate a mature methodology for designing and analyzing flight control laws for aircraft with large numbers of highly distributed control actuators and sensors—for example, shape memory alloys and piezoelectrics.
- Demonstrate a mature methodology for using information of different degrees of reliability without compromising flight safety (e.g., using data from what would traditionally be considered non-flight-critical systems within an inner control loop).
- Demonstrate long-term learning so that adaptation would only need to be used in novel situations. For example, following damage, the system adapts the first time it enters a particular part of the flight envelope but does not need to readapt if it leaves that part of the envelope and returns.
- Validate complex nonlinear systems to seek out worst-case scenarios that may not be identified with exhaustive testing.

Relevance to Strategic Objectives

Capacity (3): Advancing the state of the art in propulsion and flight control will allow manned and unmanned aircraft to operate more safely, thereby permitting UAV flight operations over highly populated areas and improving the ability of all aircraft to operate in poor weather conditions.

Safety and Reliability (9): Advanced propulsion and flight control will improve the ability of aircraft to continue operating in spite of control upsets, atmospheric disturbances such as gusts and turbulence, and damage (either natural or terrorist induced).

Efficiency and Performance (9): Advanced propulsion control increases engine efficiency, and flight control techniques such as relaxed static stability or de facto stability can improve range.

Energy and the Environment (3): Advanced propulsion control can reduce engine emissions.

Synergies with National and Homeland Security (3): Advanced propulsion and flight control can improve mission capability, safety, and supportability, which are important to military aircraft.

Support to Space (9): The intelligent and adaptive VMS for advanced propulsion and flight control directly applies to launch vehicles, spacecraft, and planetary landers and reentry vehicles.

Why NASA?

Supporting Infrastructure (3): NASA has a significant investment in high-quality vehicle system integration laboratories, flight simulators, and flight test facilities that are equal to any in DoD or industry and superior to any in academia.

Mission Alignment (9): This Challenge directly aligns with and enhances legacy NASA research in the stability and control of aircraft.

Lack of Alternative Sponsors (3): R&T related to advanced propulsion and flight control is being done by DoD, industry, and academia. However, these efforts are specialized to military aircraft and are not unified in objectives and scope.

Appropriate Level of Risk (9): This Challenge faces moderate to high risk.

D5 Fault-tolerant and integrated vehicle health management systems

Development of integrated vehicle health management (IVHM) system technologies is key to the acceptance of the automation needed in the transformation of the air transportation system. The technology provides an increased capability to accurately discover and assess system faults and reconfigure or recover from them. Although highly integrated, health management aspects consist of related components: fault detection and isolation, recovery and reconfiguration, and condition-based maintenance (CBM). In addition, modeling plays an important role in the development of these functions (Garg, 2005; Litt et al., 2005; Tandale and Valasek, 2006).

Fault detection, isolation, recovery, and reconfiguration

Fault detection, isolation, recovery, and reconfiguration involve processes and approaches that enable robust detection of faults from measured or estimated error residuals and isolation of faults with minimal latency in the presence of noise and environmental effects during aircraft operation. Fault detection, isolation, recovery, and reconfiguration are platform specific and should cover all flight regimes and mission types. Recovery and reconfiguration systems are developed with regard to the possibilities of faults, the nature of the latency of the fault detection and isolation system, and the controls available for recovery and reconfiguration. Redundancy management strategies for avionics and the airframe directly influence options for recovery and reconfiguration.

Condition-based maintenance

CBM involves maintenance processes and capabilities derived from real-time assessment of aircraft system conditions obtained by software from embedded and redundant sensors. The combination of software and sensors can create important communications and bandwidth challenges. More robust diagnostics and prognostics are needed to achieve the goal of CBM, which is to perform maintenance only on evidence of need, to prevent a failure that would reduce aircraft availability. In addition, CBM includes processes that couple real-time assessment of system and component performance with ground- and air-based logistics to improve aircraft system readiness and maintenance practices. CBM is a form of proactive equipment maintenance that forecasts incipient failures. CBM also aims to ensure safety, equipment reliability, and reduction of total ownership cost. Fault tolerance is achieved when CBM is married to decision strategies for safe and reliable operation of manned and unmanned aircraft.

Modeling

Physics-based models of sensors, actuators, avionics, components, and vehicle flight dynamics contribute to the development of methods for forecasting aircraft system performance, thereby helping to uncover faults. In addition, these models can be used for examining architectures and control strategies to reconfigure systems and ensure safety and reliability.

An aircraft is a very complex system. While individual fault-tolerant functions can be set up for each subsystem, the value of fault-tolerant designs is maximized when the system is modeled as a whole, since the behavior of each subsystem can influence that of other subsystems. The advantage of working with a total system model lies in the ability to discover a fault through its effects on other parts of the system before it is discovered in the individual subsystem itself. One primary thrust of fault-tolerant technology development is to identify system models that characterize the behavior of systems properly without developing an overly detailed and unnecessary representation. In other words, an optimum system is not a collection of optimized subsystems.

To advance the state of the art in fault-tolerant aircraft systems, fundamental R&T is required in the three topics above to develop a more robust image of the state, or health, of an aircraft in the presence of uncertainty. With a better model of itself, the aircraft can trace back system anomalies through the multitude of discrete state and mode changes to isolate aberrant behavior. Fault-tolerant systems combine simple rule-based reasoning, state charts, model-free monitoring of cross-correlations among state variables, and model-based representations of aircraft subsystems. Together, these models form a hybrid system model. Advances in computing resource technology have allowed hybrid system models to run in real time.

Fault-tolerant aircraft systems, coupled with CBM, may improve aircraft safety and reduce aircraft life-cycle maintenance and ownership costs. Critical research tasks include developing (1) robust and reliable hardware and software tools for monitoring components, detecting faults, and identifying anomalies; (2) prognosis analysis tools for predicting the remaining life of key components; (3) approaches for recovering from detected faults, including reconfiguration of the flight control system for in-flight failures of manned and unmanned aircraft; and (4) low-cost, lightweight, wireless, self-powered sensors with greater memory and processing capability. Key milestones include

- Specify nominal models and model behavior, interface, and test requirements for component and integrated system capability affected by degraded or failed operation of a representative subset of avionics and flight system components. Define suitable thresholds for levels of degraded and failed operation for component-level and system-level operations.
- Work with aircraft subsystem and flight system vendors to specify parameters that are candidates for maintenance logging. Develop models and compact representations that can incorporate measurements of these parameters in near real-time and develop thresholds that can be used for on-demand maintenance activities.
- Evaluate component capability in a simulated environment (ground test and hardware in the loop). That is, take a particular subsystem, such as a real landing gear system that has been represented by an appropriate behavioral model as specified and insert simulated faults to test for proper operation of the health monitoring system. Perform these tests for all representative subsystems that were specified above.
- Evaluate integrated system capability in a simulated environment. Take the subsystem health models previously specified and insert faults, preferably ones that were not detected as quickly as necessary by the individual component models that were evaluated in the above set of tests, and use the system models in order to evaluate the efficacy of their integrated operation.
- Test component and integrated system capability in a flight environment.

Relevance to Strategic Objectives

Capacity (3): Knowing the health of key components of an aircraft system reduces aircraft downtime and thus improves capacity. Fault-tolerant systems increase airport capacity through improved on-time dispatch of a flight.

Safety and Reliability (9): This Challenge addresses a primary component of safe and reliable operation. Monitoring the performance of key aircraft components significantly improves overall system safety and reliability and reduces uncontrolled flight into terrain for manned and unmanned aircraft.

Efficiency and Performance (3): With improved fault tolerance, overall flight performance is enhanced because faults can be isolated, thus ensuring robust operation of the aircraft. More efficient use of maintenance resources reduces aircraft downtime.

Energy and the Environment (1): Improved fault tolerance reduces life-cycle maintenance and operation costs and makes more efficient use of parts and supplies. This reduces environment effects, but only to a small degree.

Synergies with National and Homeland Security (3): Fault tolerance is important to military aircraft.

Support to Space (9): Fault-tolerant architectures for aircraft will be of great use to spacecraft systems, and fault tolerance has a major impact on space travel.

Why NASA?

Supporting Infrastructure (9): NASA has done R&T related to this Challenge and has a unique capability in applying fault tolerance to space applications. NASA has unique propulsion test facilities that would be critical for characterizing drive trains and engines for aircraft and rotorcraft. In addition, NASA has unique modeling and simulation capabilities that support fault-tolerant aircraft system modeling.

Mission Alignment (9): This research will benefit aeronautics in general, and NASA has often done similar research.

Lack of Alternative Sponsors (3): While industry and the military are looking at technology relevant to this Challenge, NASA has assembled a core competency that is unmatched for civil aircraft applications, especially for rotorcraft. NASA support is essential to address civil aeronautics applications.

Appropriate Level of Risk (9): More data are needed to determine how fault-tolerant systems impact the life-cycle costs of civil aircraft. Some information is available on how such systems can improve aircraft safety, especially for rotorcraft.

D6 Improved onboard weather systems and tools

Pilots—and the avionics software that provides in-flight, four-dimensional trajectory replanning and commands to the pilot or autopilot—require additional weather information to minimize the impact of weather on the control of flight in heavy traffic. Basic research is needed to determine the most cost-effective way of integrating real-time weather information into four-dimensional, integrated control of flight. This information might include information from data links with ground sites and other aircraft and weather video from ground stations and satellites (Bokadia and Valasek, 2001; Lampton and Valasek, 2005, 2006).

Other aircraft could provide information about geospatial position, wind, icing conditions, turbulence, lightning, and precipitation, as well as imagery from radars and other sensors. Data links with the ground could provide actual and forecast information on winds at different flight levels, pressure, icing potential, precipitation, ground-level temperatures, weather fronts, severe weather, airport surface conditions, and other information from significant meteorological information reports (SIGMETs), pilot reports (PIREPs), meteorological aviation reports (METARs), terminal area forecasts (TAFs), imagery from satellites and radars, and so on. Key milestones include

- Develop robust and reliable data links for collecting information from onboard sensors.
- Develop processes and tools for integrating weather information from onboard sensors and data links to the ground and other aircraft.
- Demonstrate effectiveness in practical decision-support applications relating to weather, with varying levels of information quality and uncertainty.

Relevance to Strategic Objectives

Capacity (9): Improving the quality and use of weather information will enable aircraft to avoid or fly through weather more effectively, which will reduce delays due to weather.

Safety and Reliability (9): Improving the quality and use of weather information, including information on runway conditions, will reduce the number of aircraft accidents caused by weather. Pilots will be less likely to fly into weather that they or their aircraft cannot handle.

Efficiency and Performance (3): Fuel consumption can be reduced by flight plans that incorporate real-time information on winds aloft to maintain the desired four-dimensional flight trajectory.

Energy and the Environment (1): This Challenge has little impact on this Objective. There might be some indirect benefit through the reduction of emissions or ground noise by optimizing flight plans, allowed by improved onboard weather systems and tools.

Synergy with National and Homeland Security (1): This Challenge would also benefit DoD and DHS flight operations involving civil airspace.

Support to Space (1): This Challenge has little or no application to this Objective.

Why NASA?

Supporting Infrastructure (9): NASA has an outstanding research facility for icing tests and evaluation and the infrastructure to develop and test weather-related tools.

Mission Alignment (9): This Challenge is central to NASA s safety and capacity mission.

Lack of Alternative Sponsors (3): Some airlines have invested in developing capabilities relevant to this Challenge, and the FAA and Air Force are also interested. However, these efforts are limited in comparison to what NASA could do.

Appropriate Level of Risk (3): Weather-related tools exist, but integration into other systems, especially onboard systems, is needed. This Challenge faces low risk, and transfer to industry is likely, because industry is developing some tools related to the integration of weather information.

D7 Advanced communication, navigation, and surveillance (CNS) technology

The capacity of the air transportation system is dependent on minimum spacing requirements for safe operation. Minimum spacing depends on many factors, including the capability of each aircraft to precisely fly a predetermined, geospatially time-referenced flight path.

Advanced, integrated, accurate, secure, and reliable CNS capabilities are required for network-centric operations, which can increase capacity in very high density airspace. Each aircraft may be considered a node in a network-centric, distributed, fault-tolerant ATM system. Communications between nodes (aircraft to aircraft, aircraft to ground, and aircraft to satellite to ground) must be highly reliable. (For example, the probability of a missed or incorrect message should be less than 10^{-7} per flight hour, depending on the consequence of the fault). Safe, secure, accurate, and certifiable CNS technologies that provide required capabilities are needed.

More precision aircraft navigation, coupled with the precise six-dimensional[5] guidance algorithms used in advanced flight management systems, will enable reduced spacing between aircraft operating en route and in the terminal airspace. CNS system functions must be tightly coupled in terms of information integrity, and they should allow pilots to operate cooperatively with ground systems without controllers continuously in the control loop. The CNS should transmit navigation, guidance, and other sensor data to other aircraft and ground operation centers via multichannel data links while, at essentially the same time, they receive similar information about other aircraft, the weather, airport conditions, etc. This information can prevent accidents by revealing the current and future status of other aircraft, weather

[5]The six dimensions refer to three position coordinates and three velocity vectors to define aircraft location, speed, and direction of motion.

phenomena, terrain, buildings, and vehicles on the ground at airports. This Challenge should also increase the affordability of onboard avionics to encourage aircraft owners and operators to procure more capable avionics. This Challenge encompasses the following CNS issues:

- Communications issues.
  —Fault-tolerant network connectivity and security.
  —Dynamic network control and reconfiguration.
  —Quality of service.
  —Spectrum allocation and usage.
  —Adequate communication bandwidth.
  —Required communications capability as a function of geospatial location and phase of flight.
- Navigation issues.
  —High-precision, six-dimensional estimate of aircraft state as a function of time.
  —Integration of satellite navigation with other navigation modes.
  —Navigation system capability, including reliability and quality, of input signals.
  —Functional integration of navigation system with guidance and flight control systems to ensure high-integrity, integrated control of flight during automatic and manual modes.
- Surveillance issues.
  —Capability of data links to provide accurate time-referenced data from navigation systems, guidance systems, and other sensors when interrogated by external systems or periodic broadcast.
  —Handling of multiple, simultaneous interrogations using multiple channels to provide high-integrity, secure data.
  —Processing and reacting to incoming data about other aircraft, hazardous weather, etc.
  —Continuous improvement in situational awareness through advanced sensors, communication links, and human–system interfaces.

Key milestones include

- Simulate avionics on an individual aircraft to determine the capability of each avionics function (communication, navigation, guidance, control, and surveillance).
- Demonstrate (1) fault-tolerant degradation of CNS capability (in terms of accuracy and availability of modes) and (2) processes needed to ensure that the individual aircraft can still transmit the needed aircraft state information and receive information and air traffic control commands with an extremely low probability of communication error.
- Evaluate different tracking and control algorithms with various faults that could occur in either the ATM system or airborne aircraft to determine whether the algorithms are able to detect the faults, identify them, and recover from them by reconfiguring the system in which the fault occurred as well as other systems to provide a satisfactory level of service.
- Document the feasibility of using space-based communications and surveillance as both a primary and backup means of ATM.
- Demonstrate modeling and real-time simulation using distributed control centers and different traffic levels, ranging from the current peak hourly load of about 6,000 airborne aircraft in the continental U.S. airspace to a predicted hourly load of 18,000 airborne aircraft, using current demand patterns. This effort is required to verify that the network of communication links, processing nodes in the network, and control algorithms provides the desired capacity while satisfying safety criteria.
- Demonstrate a means to provide seamless information flow between an aircraft s multiband antenna and the fiber-optic local area network that manages the information flow between aircraft systems and the radio channels.
- Demonstrate a robust IVHM system that detects permanent and transient onboard system faults and communicates system status to pilots and ground systems.
- For aircraft equipped with autothrottles, develop performance algorithms linked to aircraft dynamics to maintain the approved flight trajectory while minimizing fuel consumption. For aircraft that are not equipped with autothrottles, document the information required by the flight management system to generate speed commands to be displayed to pilots while minimizing pilot workload.
- Develop an air-ground communication protocol that (1) optimally allocates functions among pilots, avionics, air traffic controllers, and automated ground systems and (2) includes a means to alert ground systems and controllers that the data link or an onboard system has failed. This will require control algorithms that can handle multiple failures in terms of controlling the aircraft with the failures as well as adjacent traffic to minimize the impact on airspace capacity and efficiency.

Relevance to Strategic Objectives

Capacity (9): Tripling the number of aircraft in the airspace requires reducing the uncertainty of six-dimensional aircraft state (position and velocity) to less than one-third of the current required navigation precision of 0.1 nautical mile. Time-tagged state information must be broadcast so that adjacent aircraft as well as ground systems know the relative position and velocity of aircraft and each aircraft s deviation from its planned flight trajectory.

Safety and Reliability (9): This Challenge will provide fault-tolerant aircraft and ground systems that will permit safely reducing separation standards.

Efficiency and Performance (9): This Challenge will enable aircraft to fly flight trajectories that minimize fuel consumption.

Energy and the Environment (3): This Challenge will enable aircraft to fly flight trajectories that reduce noise and emissions.

Synergy with National and Homeland Security (3): This Challenge will benefit military aircraft that operate aircraft in civil airspace.

Support to Space (3): The systems developed for operation in Earth s airspace and atmosphere should have application to operations in a martian atmosphere.

Why NASA?

Supporting Infrastructure (3): NASA research centers have the engineering skills, computing and simulation facilities, and test aircraft to develop the technologies required to make advanced CNS a reality.

Mission Alignment (9): This Challenge is very relevant to NASA s mission.

Lack of Alternative Sponsors (3): Industry and federal government agencies are developing some CNS technologies, but they have lagged behind European development of some new technologies required to operate in the global airspace.

Appropriate Level of Risk (3): The individual technologies are low risk. The best methods of integrating these technologies remains to be developed and demonstrated.

D8 Human–machine integration

The ever-increasing demand for air transportation, combined with the rapid pace of technological change, poses significant challenges for effective integration of humans and automation. For the foreseeable future, humans will continue to play a central role in key decision-making tasks that directly influence the efficiency and safety of civil aviation. As technology evolves, it may be anticipated that the role of humans and the nature of their task will change accordingly. In order to maintain or improve upon existing standards of performance and safety, it is critical that the allocation of functions between humans and automation and the design of the human–machine interface be optimized based on a solid foundation of scientific principles that reflect our best understanding of human sensory, perceptual, and cognitive processes. Human–machine integration should remain an important element of NASA research directed toward civil aeronautics applications.[6] However, the emphasis should be shifted from development and testing of specific input and output devices toward more fundamental research involving modern instruments that measure brain physiology. Research should also include voice command and recognition technology, coupled with increased machine contextual understanding, to reduce workload. This will help define the future role of humans in complex, highly automated systems. Key milestones related to human–machine integration methods and tools include

- Develop improved system engineering processes and tools for determining optimum roles of humans and automation in complex systems and demonstrate the benefits of this improved methodology in a trial application. This milestone should include provisions for dynamic human–machine task allocation and monitoring of human performance by machines (e.g., automated terrain avoidance).
- Conduct fundamental research on the causes of human error and on human contributions to safety and document design guidelines that will (1) help minimize the potential for design-induced error and (2) facilitate positive human intervention in the event of system failures. Transfer these guidelines to government program offices and industry.
- Develop constructive models of human performance and decision making and validate model predictions against objective performance data acquired in high-fidelity human-in-the-loop flight simulation experiments.
- Develop and demonstrate rapid prototyping tools that enable comparative evaluations of alternative automation schemes early in system development.
- Develop and validate a technique for integrating human reliability estimates into system safety and reliability analyses.

Key milestones related to human–machine integration technologies for vehicle applications include

- Develop and test enabling technologies for pilot workload management and reduced crew operations (e.g., improved human–machine integration for a flight management system) while keeping pilot awareness at the proper level.
- Develop display concepts for maintaining operator situational awareness while monitoring highly automated processes. Demonstrate the ability of operators to rapidly and accurately intervene in the event of system failures.
- Develop technologies and/or display concepts enabling effective fusion of information from multiple sources, including real-world and synthetic imagery (i.e., augmented reality). Demonstrate the effectiveness of these concepts in practical decision support applications with varying levels of information quality and uncertainty (in terms of accuracy, timeliness, etc.).
- Develop and demonstrate technologies for machine vision (image-based object detection).

[6] J. Vagners, professor emeritus, aeronautics and astronautics, University of Washington, Presentation to Panel D on November 15, 2005.

- Develop tools and metrics to compare effectiveness of machine and human operators in see-and-avoid tasks to improve machine performance.

Relevance to Strategic Objectives

Capacity (3): This Challenge will address human performance limits that constrain overall performance of the air transportation system, such as aircraft separation, wake vortex avoidance, operations in reduced visibility, high-speed turnoffs, baggage and cargo handling, aircraft maintenance and servicing, etc.

Safety and Reliability (9): Human factors are the predominant cause of accidents and incidents in civil and military aircraft operations. Operational safety statistics show that 65 to 75 percent of mishaps are attributable to human error. This Challenge will reduce human error.

Efficiency and Performance (9): Reducing the workload of pilots and controllers would make more efficient use of human and automation resources.

Energy and the Environment (1): This Challenge has little or no impact on this Objective.

Synergies with National and Homeland Security (3): This Challenge will address issues related to command and control of complex, highly automated systems, situation awareness, and safety of flight operations, all of which are of interest to DoD. Elements of this Challenge that address information management and decision support systems (e.g., data mining, decision making under uncertainty, modeling and prediction of human behavior, etc.) are also relevant to DHS.

Support to Space (3): Elements of this Challenge directed toward ATM improvements may have applicability to ground-based control of space systems. Some research related to advanced human–machine integration devices (e.g., synthetic vision) may also be beneficial to ongoing manned spaceflight programs.

Why NASA?

Supporting Infrastructure (3): NASA has substantial capability (personnel and facilities) to do world-class research in human–machine integration. The facilities at NASA Ames and Langley Research Centers provide a unique environment for integrated, human-in-the-loop simulation of both flight deck and ATM technologies. These facilities have been specifically designed and instrumented for evaluation of advanced concepts for human–machine integration in a high-fidelity operational environment.

Mission Alignment (9): Advanced human–machine integration research is a mainstream activity for NASA Ames and Langley Research Centers and is very relevant to NASA s mission.

Lack of Alternative Sponsors (3): Some human–machine integration issues might be addressed by DoD labs, industry, or academia, if not addressed by NASA. However, research on fundamental human–machine integration principles and research directed specifically at civil aeronautics would probably be neglected without NASA leadership. The FAA historically looks to NASA to perform human–machine integration research, particularly as it relates to ATM.

Appropriate Level of Risk (9): Human–machine integration represents a broad spectrum of moderate- to high-risk technical challenges with both near- and far-term implications.

D9 Synthetic and enhanced vision systems

Synthetic and enhanced vision systems provide an out-the-window view of terrain, obstacles, and traffic. These systems can also be used as flight crew interfaces for flight trajectory and planning operations (Kelly et al., 2005). The synthetic vision systems that use databases to generate terrain and obstacles require high-fidelity, high-integrity information and a self-healing capability. Enhanced vision systems use forward-looking sensors such as infrared, radar, and laser ranging to allow the flight crew to visualize the real world when visibility is hindered. Currently, vision systems are limited by weather, human factors issues, and other issues. New sensors and improved sensor fusion are needed.

A combined synthetic and enhanced vision system has future potential as a navigation, approach, and landing sensor. The ability to "see" the airport in poor weather has the potential to reduce the likelihood of a go-around. Information fusion that exploits the capabilities of sensors and compensates for their deficiencies is needed, and the immature state of this art represents the most difficult obstacle to achieving these benefits.

Synthetic and enhanced vision systems are also intended to aid airport surface operations in poor weather, reducing runway occupancy and taxiing errors and reducing gate-to-gate travel time. Research topics of interest are as follows:

- Database integrity and quality
- Information fusion
- Object detection and avoidance
- Human–machine interface issues
- Verification of accuracy, fault tolerance, and reliability

Key milestones include

- Prepare an accurate and complete terrain and obstacles database and demonstrate real-time database monitoring and error correction.
- Develop procedures and rules for fusing image information from multiple imaging sensors as well as stored terrain data and traffic; identify common viewing parameters; and determine what role enhanced vision systems and synthetic vision systems should play in an integrated system.

- Demonstrate increased situational awareness and alerting to avoid air traffic, airport surface traffic, wires, and cables.
- Demonstrate displays that (1) eliminate image fusion artifacts that lead to misleading information and (2) present conformal information to pilots in a way that facilitates its transition to the outside world.
- Demonstrate tools for verifying database accuracy, fault tolerance, reliability, and overall system accuracy.

Relevance to Strategic Objectives

Capacity (3): This Challenge increases capacity due to better area navigation performance in the terminal area and improved surface operations, which increase capacity by compensating for the effects of bad weather and night vision constraints.

Safety and Reliability (9): Accurate synthetic and enhanced vision systems can increase safety dramatically during approach, landing, and ground operations. The intuitive information provided on advanced display is more easily understood than needles and gauges used in nonglass cockpits, especially with inexperienced pilots.

Efficiency and Performance (3): Terrain and obstacle information, combined with flight trajectory information, can result in more efficient flight paths.

Energy and the Environment (1): This Challenge has no impact on this Objective.

Synergy with National and Homeland Security (1): This Challenge does not apply to this Objective.

Support to Space (3): The technology developed for this Challenge can also be used by vehicles landing on other planets.

Why NASA?

Supporting Infrastructure (9): NASA has supported R&T relevant to this Challenge and has relevant expertise, aircraft platforms, and other test and evaluation facilities.

Mission Alignment (9): This Challenge is consistent with NASA s commitment to aviation safety.

Lack of Alternative Sponsors (3): Industry and DoD support R&T relevant to this Challenge. NASA s involvement is needed to provide overall leadership and to continue to push the envelope.

Appropriate Level of Risk (3): This Challenge faces low risk. Some commercial development has already occurred.

D10 Safe operation of unmanned aerial vehicles in the national airspace

The use of UAVs for a variety of civil applications (e.g., farming, communications relays, border monitoring, power line and pipeline monitoring, and firefighting) will continue to increase. Flight operations of military UAVs in civil airspace is also expected to increase. To facilitate these operations, UAVs should be integrated into the air transportation system. This requires them to be at least as safe as manned aircraft.

Most UAV technologies, capabilities, and processes are shared with manned aircraft and require research in several key topics, including the following four:

- *Aircraft*. Automation, system upgrade issues, and communications systems, all of which are distinct from those for manned aircraft.
- *Human–machine interaction*. Function allocation, human interface design, situational awareness, training, and required level of proficiency in the remote operation of the aircraft.
- *Maintenance and support*. In matters where UAVs differ distinctly from traditional aircraft.
- *Flight operations*. Sense- or see-and-avoid issues, person-to-person interfaces between operators and controllers, assurance of positive control of the aircraft (especially with highly automated UAVs that are not directly controlled by ground-based operators in real time), and automated contingency management.

Key milestones include

- Develop and demonstrate secure, reliable communications as well as procedures for interaction between UAVs and air traffic controllers.
- Design, develop, and demonstrate human interfaces for remote UAV operators under conditions extant in the air transportation system.
- Develop and test training programs for remote UAV operators.
- Develop and demonstrate sense-and-avoid technologies for UAVs.
- Demonstrate technologies for maintaining positive control of UAVs under adverse conditions.
- Develop and demonstrate automated contingency management for control of UAVs.

Relevance to Strategic Objectives

Capacity (3): This Challenge will enable more UAV flight operations in civil airspace. There is little impact on the movement of people but might be a significant impact on freight movement in the future.

Safety and Reliability (9): This Challenge is essential for safe and reliable operation of UAVs in civil airspace, both controlled and uncontrolled.

Efficiency and Performance (3): It takes months to obtain a waiver to allow UAV operations in civil airspace. This Challenge should help alleviate this situation and facilitate efficient commercial UAV operations.

Energy and the Environment (1): This Challenge has little or no impact on this Objective.

Synergies with National and Homeland Security (9): The ability to routinely operate UAVs in civil airspace will enhance national defense and homeland security operations.

Support to Space (1): This Challenge has little application to this Objective, although some synergies may exist with regard to automation and communications for spacecraft vehicle control.

Why NASA?

Supporting Infrastructure (3): NASA has more experience than any other entity in the test and evaluation of UAV systems.

Mission Alignment (9): This Challenge is very relevant to NASA s mission.

Lack of Alternative Sponsors (3): Industry is addressing DoD-related issues regarding airframes, operators, and maintenance. The commercial and government applications arena is hindered by operational issues that NASA can effectively address.

Appropriate Level of Risk (3): This Challenge faces low risk.

D11 Secure network-centric avionics architectures and systems to provide low-cost, efficient, fault-tolerant, onboard communications systems for data link and data transfer

As NASA moves into the network-centric vision of the future, data link assurance will become increasingly important. Threats to the integrity of information can be grouped into two categories: natural threats and malicious threats. Natural threats are associated with unintended system failures and include hardware and software flaws, lightning strikes, cosmic rays, and human error. Malicious threats are intelligent directed attacks. Historically, the former have posed the greater threat. However, as future aircraft become more network-centric, a new class of malicious threats could become increasingly destructive.

Data must be considered a valuable and critically important asset. Data loss and corrupt data can cause significant problems, especially in cooperative networked systems. In addition, data separation is required to protect International Traffic in Arms Regulations (ITAR) data from unauthorized disclosure. Considerations such as ITAR are increasing the need for avionics architectures that allow different nodes to communicate with each other over encrypted data links at different levels of security. Traditional approaches for assuring the security of networked information, such as the Transmission Control Protocol (TCP), have problems in high-latency environments such as deep space and parts of the air transportation system. DARPA has been developing a trusted key distribution mechanism, but it is unknown if this mechanism has similar problems with operating in such an environment. It would allow for NASA to address the needs of both legacy and new systems to function in a network-centric manner. Key milestones include

- Develop fundamental system requirements, architecture, and system logic that are compatible with current and future network-centric system requirements.
- Complete fundamental research necessary to develop and incorporate encryption techniques, threat detection, and counterthreat strategies.
- Develop simulation capabilities for evaluation and demonstration of certain high-performing strategies in the execution of realistic system architectures and applications.
- Develop requirements flowdown to all affected aircraft systems, such as advanced CNS.
- Develop requirements and methodology to support verification, validation, and certification of future systems incorporating this technology.

Relevance to Strategic Objectives

Capacity (9): This Challenge will increase capacity by developing key technologies and capabilities related to secure network communications, cooperative distributed networking systems, networked weather systems, and the like.

Safety and Reliability (9): Unreliable and insecure data links increase the likelihood of catastrophic failure. Secure data links prevent malicious and accidental corruption of data.

Efficiency and Performance (9): Improved communications security allows full exploitation of available communication infrastructure.

Energy and the Environment (1): This Challenge has little or no impact on this Objective.

Synergy with National and Homeland Security (9): Reliable and secure data links are required for national and homeland security to prevent both malicious and/or accidental corruption of data, especially with missions involving UAVs.

Support to Space (3): Reliable and secure data links are required for space missions to prevent both malicious and/or accidental corruption of data.

Why NASA?

Supporting Infrastructure (3): NASA has strong credentials in avionics architectures, network architectures, and encryption technology. NASA also has domain expertise to evaluate the applicability of these technologies.

Mission Alignment (3): This research will directly support multiple R&T Challenges and benefit military and civil aviation, as well as future applications in space.

Lack of Alternative Sponsors (1): Industry and DoD labs are developing technology related to this Challenge, but it is predominately focused on military systems. The commercial information technology business sector is very active in commercial encryption and networking technologies.

Appropriate Level of Risk (3): Near-term research can address issues related to this Challenge, and the results can be transferred to future civil and military applications.

D12 Smaller, lighter, and less expensive avionics

Today s commercial and military aircraft have benefited from a modest size, weight, and cost savings as a result of integrated avionics systems and fly-by-wire flight control systems, smaller antennas, smaller sensors, and digital data buses.

The expansion of smaller and lighter aircraft (in particular UAVs) resulted in development of significantly smaller and lighter avionics. While not common, entire systems weighing less than 1 pound have demonstrated that basic avionic functionality (navigation, communication, and autoflight) can be fit into a package (or set of packages) that are much smaller than and very different from conventional commercial and military avionics.

To maximize the efficiency and performance of future commercial and military aircraft, new technology is needed that significantly reduces the cost, size, and weight of current avionics as well as their supporting installation infrastructure (by minimizing or eliminating equipment mounting hardware and aircraft wiring). Key milestones include

- Demonstrate technologies that provide wireless onboard communications.
- Demonstrate methods to reduce processing requirements and power requirements.
- Demonstrate methods to improve avionics system capability, integrity, and reliability using low-cost components/sensors, including greater use of commercial off-the-shelf (COTS) components.
- Demonstrate greater use of microcontrollers as main processors and in distributed processing.
- Document common data standards that have broad application and usage.

Relevance to Strategic Objectives

Capacity (1): This Challenge could prompt some aircraft owners (especially in general aviation) to install more avionics, which would increase aircraft capability and indirectly increase capacity, although this effect would likely be small.

Safety and Reliability (3): Low-cost avionics could prompt some aircraft owners (especially in general aviation) to install more avionics, which would increase safety. However, the incorporation of COTS technologies into modern avionics systems has met greater scrutiny from regulatory agencies than ever before. The industry needs an affordable means to improve the performance, quality, and safety of increasingly complex avionics systems. These advanced avionics should come with or enable inherently fewer failure modes.

Efficiency and Performance (9): One pound of dead weight on a commercial transport increases fuel costs on the order of $100 per aircraft per year. Transport aircraft typically carry 200 pounds of avionics, not counting associated wiring. Smaller aircraft have a larger proportion of their weight in avionics, so the savings in fuel costs should be a larger proportion of total fuel costs. In addition, ultralight aircraft can have longer mission times if they can carry less weight. Common standards that permit cross-product strategies, such as wireless data protocols and transfer media reduce costs. ARINC standards are good examples of common protocols, but generally they focus on airline applications.

Energy and the Environment (3): Avionics weight savings reduce fuel consumption and will have a positive effect on the environment.

Synergies with National and Homeland Security (3): Technologies that enable weight and size savings, specifically wireless technologies that interconnect onboard systems and components, will need to be sufficiently secure and reliable to maintain aircraft safety. New systems that meet these needs may result in by-products that can be used in ground-based vehicles and fixed-base stations.

Support to Space (9): Smaller and lighter avionics are enablers for future space flight, especially for missions that would benefit from significantly reduced avionics power requirements.

Why NASA?

Supporting Infrastructure (3): The Jet Propulsion Laboratory (JPL) conducts relevant research, but its focus is space-based. This Challenge would use technologies developed for space to support aeronautics.

Mission Alignment (3): This Challenge will benefit the complete civil aviation community and have application in future space travel.

Lack of Alternative Sponsors (3): Industry is developing smaller and less expensive avionics, but they are geared toward unique applications like UAVs. In general, manufacturers of commercial and military aircraft are slow to make revolutionary changes in technology without a clearly understood business case or a clear assessment of risk; regulatory constraints are a major factor.

Appropriate Level of Risk (3): This Challenge faces low risk.

D13 More efficient certification processes for complex systems

Certification of aircraft and aircraft systems has focused on airworthiness using process-based standards. Products for which the processes have been followed are assumed to have acceptable quality. Many of the required processes in the standards, however, are expensive and time-consuming. In addition, following a good process does not necessarily imply the product is safe.

An alternative approach to process-based certification is to certify the product itself. Product-based certification and more efficient ways to do process-based certification could greatly reduce the time and cost of creating aircraft systems while potentially increasing safety. How to do such certification, particularly for software-intensive systems, is unknown, and research that could provide a valid and demonstrated basis for product-based certification could increase quality assurance while decreasing costs and could significantly influence industry standards and FAA advisory circulars.

Recently, a third, performance-based approach to specifying certification requirements has been applied to some systems. In this approach, a required performance level is specified rather than the process required to produce it or ways to evaluate the product. An example is required navigation performance (RNP), in which the performance level of certain navigational systems is specified. R&T is still needed, however, to demonstrate that the system will satisfy the performance requirement.

A final problem occurs when completely new technologies or procedures, such as reduced aircraft separation, are introduced in the air transportation system. Changes foreseen as necessary to transform the system and to solve critical problems in capacity involve significant new technology and operational procedures. Assurance of safety in past systems has relied on making few major changes and relying on historical data and experience, which will not be available when major changes are implemented over a short period of time. New, revolutionary approaches will be required to provide the necessary level of confidence in these new systems. Key milestones include

- Validate that following specific processes will produce required assurance levels.
- Demonstrate processes for certifying products such as software, where testing is unable to provide required levels of confidence.
- Demonstrate approaches to assuring that required performance levels will be achieved in complex systems, despite failures or environmental disturbances.
- Demonstrate approaches to ensuring the safety of proposed changes to the national airspace system for which historical data and prior experience are not available.

Relevance to Strategic Objectives

Capacity (3): New enhancements to the air transportation system that increase capacity will need to be certified and shown to be safe.

Safety and Reliability (9): Because the goal of certification is to ensure safety, more efficient and effective certification approaches could have a major impact on safety.

Efficiency and Performance (9): More efficient certification processes should reduce the number of resources required to develop and certify new aircraft capabilities, systems, and products.

Energy and the Environment (1): This Challenge has no impact on this Objective.

Synergies with National and Homeland Security (1): This Challenge has no impact on this Objective.

Support to Space (3): Some of the safety and reliability technologies developed by this Challenge will apply to space systems.

Why NASA?

Supporting Infrastructure (3): Some NASA infrastructure could be used in the evaluation of new certification approaches.

Mission Alignment (1): Certification is the responsibility of the FAA and the aircraft manufacturers, not NASA. NASA has capabilities, however, that could effectively help the FAA and industry address certification issues.

Lack of Alternative Sponsors (1): The FAA and other certification agencies have the responsibility for certification and thus interest in improvement. Aircraft and aircraft system manufacturers have great interest in this topic.

Appropriate Level of Risk (3): New certification approaches (including capability-based approaches) are feasible and are being recommended and used (e.g., RNP), so this Challenge faces low risk, but more research is needed into the effectiveness of the new and proposed approaches and how to implement them.

D14 Design, development, and upgrade processes for complex, software-intensive systems, including tools for design, development, and validation and verification

The introduction of software and digital components has allowed the development of increasingly complex systems but at the same time has required changes and additions to basic engineering approaches and methodologies. Basic research in new tools and techniques is needed for designing and testing software-intensive systems and for maintaining and upgrading them over time. For example, most software cannot be exhaustively tested, and the verification difficulties become even greater when nondeterministic artificial intelligence techniques are employed. There is a need for new ways to provide assurance, particularly for critical systems.

One technology relevant to this Challenge is model-based development, whereby models that can be executed and analyzed are constructed prior to system implementation and construction. Model-based development potentially can augment the detection of conceptual design errors early in development, when they are much less expensive to correct; decrease development time and risk; and allow for greater reuse of system engineering effort. Research should strive to improve analysis and specification of design rationale, visualization and simulation tools, and so forth. Key milestones include

- Develop easily used and reviewed modeling languages.
- Develop automated design and code generation.

Relevance to Strategic Objectives

Capacity (3): The development of new aircraft capabilities is increasingly being driven by the requirement to develop and upgrade software. Software development is a component of most approaches to increasing capacity, but it is not the most critical component.

Safety and Reliability (9): Because the behavior of complex systems is increasingly controlled by software, software can have a significant impact on safety and reliability.

Efficiency and Performance (3): Software costs are a driving factor in design and development. Improving design, development, and upgrade processes would increase efficiency and performance.

Energy and the Environment (1): This Challenge has relatively little effect on energy use and the environment, and the effect is indirect.

Synergies with National and Homeland Security (1): Software-intensive systems might be used to implement some new technologies, but the benefit to DoD and DHS would be indirect.

Support to Space (3): Some of the R&T relevant to this Challenge would apply to space control systems, but design requirements are very different.

Why NASA?

Supporting Infrastructure (1): NASA has some capable researchers in fields related to this Challenge, but NASA has outsourced most R&T relevant to this Challenge.

Mission Alignment (3): This Challenge is not well aligned with NASA s mission. Relevant tools and methodologies are applicable to any complex system, not just aerospace.

Lack of Alternative Sponsors (1): Industry, DoD, and academia are developing many tools relevant to this Challenge.

Appropriate Level of Risk (1): This Challenge faces very low risk. Many relevant tools and techniques exist and much of the basic research has been done.

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E

R&T Challenges for Intelligent and Autonomous Systems, Operations and Decision Making, Human Integrated Systems, and Networking and Communications

A total of 20 R&T Challenges were prioritized in the Area of intelligent and autonomous systems, operations and decision making, human integrated systems, and networking and communications. Table E-1 shows the results. The R&T Challenges are listed in order of NASA priority. National priority scores are also shown.[1] This appendix contains a description of each R&T Challenge, including milestones and an item-by-item justification for each score that appears in Table E-1.[2]

E1 Methodologies, tools, and simulation and modeling capabilities to design and evaluate complex interactive systems

The U.S. air transportation system is a complex interactive system whose behavior is difficult to simulate with currently available models. Methodologies, tools, and simulation and modeling capabilities suited for the design and integration of complex interactive systems are needed to understand the air transportation system as an integrated, adaptive, distributed system that includes aircraft, ATM facilities, and airports, each with its own complex systems, all of which interact with one another, the environment, and human operators. Simulations and models for complex interactive systems are needed to accurately estimate system performance, to properly allocate resources, and to select appropriate design parameters. Additionally, the large number of possible future system designs requires models that can be reconfigured to model a wide range of design parameters.

One key barrier to developing integrated aviation systems is the lack of basic research that regulators can use to develop new certification standards and testing methodologies. Tools and methodologies that can assess the reliability and effectiveness of complex, nondeterministic, software-intensive future systems need to be developed. In some cases, this will also require changes to FAA regulations and certification standards (Aerospace Commission, 2002, pp. 2-9). This Challenge will help ensure that the right architecture and design decisions can be made in developing the air transportation system of the future. Key milestones include

- Demonstrate methodologies and tools for the design, test, and certification of a flexible, robust, safe air transportation system that is readily adaptable to changing operational paradigms suited to new and different vehicles, including unmanned air vehicles (UAVs), very light jets (VLJs), and spacecraft operating in civil airspace; communications, navigation, and surveillance capabilities; and optimization techniques.
- Demonstrate a flexible ATM model that incorporates the performance characteristics and limitations of the wide mix of present and future aircraft arriving, departing, and operating within airspace surrounding major hub airports. This model should be capable of analyzing the impacts of (1) aircraft mix and (2) operator and controller decision making and actions on system efficiency and capacity.
- Demonstrate the ability of an enhanced version of the model to assess the impact of regional weather phenomena, such as convective activity, snow, and high winds.
- Demonstrate the capability to test and certify nondeterministic systems.
- Demonstrate the ability of an enhanced version of the ATM model to assess impacts of aircraft mix and operator and controller decision making.

Relevance to Strategic Objectives

Capacity (9): The capacity of the air transportation system must double or triple over the next 20 years to keep up

[1] The prioritization process is described in Chapter 2.

[2] The technical descriptions for the first 10 Challenges listed below are the same as the technical descriptions for these Challenges as they appear in Chapter 3.

TABLE E-1 Prioritization of R&T Challenges for Area E: Intelligent and Autonomous Systems, Operations and Decision Making, Human Integrated Systems, and Networking and Communications

		Strategic Objective							Why NASA?					
R&T Challenge	Weight	Capacity	Safety and Reliability	Efficiency and Performance	Energy and the Environment	Synergies with Security	Support to Space	National Priority	Supporting Infrastructure	Mission Alignment	Lack of Alternative Sponsors	Appropriate Level of Risk	Why NASA Composite Score	NASA Priority Score
		5		3		1			1/4 each					
E1	Methodologies, tools, and simulation and modeling capabilities to design and evaluate complex interactive systems	9	9	9	9	9	3	**156**	3	9	3	9	**6.0**	**936**
E2	New concepts and methods of separating, spacing, and sequencing aircraft	9	9	9	3	3	1	**130**	3	9	3	9	**6.0**	**780**
E3	Appropriate roles of humans and automated systems for separation assurance, including the feasibility and merits of highly automated separation assurance systems	9	9	9	1	3	1	**124**	3	9	3	9	**6.0**	**744**
E4	Affordable new sensors, system technologies, and procedures to improve the prediction and measurement of wake turbulence	9	9	3	1	1	1	**104**	3	9	3	9	**6.0**	**624**
E5	Interfaces that ensure effective information sharing and coordination among ground-based and airborne human and machine agents	3	9	9	1	9	3	**102**	3	9	3	9	**6.0**	**612**
E6	Vulnerability analysis as an integral element in the architecture design and simulations of the air transportation system	3	9	9	1	9	1	**100**	3	9	3	9	**6.0**	**600**
E7	Adaptive ATM techniques to minimize the impact of weather by taking better advantage of improved probabilistic forecasts	9	3	9	3	1	1	**98**	3	9	3	9	**6.0**	**588**
E8a	Transparent and collaborative decision support systems	3	9	9	1	3	3	**96**	3	9	3	9	**6.0**	**576**
E8b	Using operational and maintenance data to assess leading indicators of safety	3	9	9	1	3	3	**96**	3	9	3	9	**6.0**	**576**
E8c	Interfaces and procedures that support human operators in effective task and attention management	3	9	9	1	3	3	**96**	3	9	3	9	**6.0**	**576**
E11	Automated systems and dynamic strategies to facilitate allocation of airspace and airport resources	9	3	9	3	3	1	**100**	3	9	1	9	**5.5**	**550**
E12	Autonomous flight monitoring of manned and unmanned aircraft	3	9	3	1	9	1	**82**	3	9	3	9	**6.0**	**492**
E13	Feasibility of deploying an affordable broad-area, precision-navigation capability compatible with international standards	9	9	3	1	3	1	**106**	3	3	3	9	**4.5**	**477**
E14	Advanced spacecraft weather imagery and aircraft data for more accurate forecasts	3	3	9	3	1	1	**68**	3	9	3	9	**6.0**	**408**
E15	Technologies to enable refuse-to-crash and emergency autoland systems	1	9	1	1	3	1	**60**	3	9	3	9	**6.0**	**360**
E16	Appropriate metrics to facilitate analysis and design of the current and future air transportation system and operating concepts	3	3	9	3	3	1	**70**	3	9	3	3	**4.5**	**315**
E17	Change management techniques applicable to the U.S. air transportation system	9	9	9	1	3	1	**124**	1	3	3	3	**2.5**	**310**
E18	Certifiable information-sharing protocols that enable exchange of contextual information and coordination of intent and activity among automated systems	3	1	9	1	9	1	**60**	3	9	3	3	**4.5**	**270**
E19	Provably correct protocols for fault-tolerant aviation communications systems	3	9	3	1	3	1	**76**	3	3	1	1	**2.0**	**152**
E20	Comprehensive models and standards for designing and certifying aviation networking and communications systems	3	9	3	1	1	1	**74**	3	3	1	1	**2.0**	**148**

with demand. The capacity of the air transportation system is not the sum of the capacities of system components, because interactions among components are complex and interactions among system components may not be synergistic. The most effective way to estimate the capacity of the many options for the future U.S. air transportation system, and thereby identify the option that best meets future capacity needs, is to use system-of-system models that capture the functional relationships within the air transportation system.

Safety and Reliability (9): Models suited to complex interactive systems are needed to understand the complex behavior of the air transportation system and to quantify safety for the current system and proposed changes to the system. These models would provide a unique and vital capability to identify safety issues, including unintended consequences, especially for radically different system configurations.

Efficiency and Performance (9): Significant increases in efficiency will also be required to satisfy projected increases in demand. Models suited to complex interactive systems are needed to understand the behavior of the air transportation system and to quantify levels of efficiency and performance for the current system and proposed changes to the system.

Energy and the Environment (9): Environment considerations (noise and emissions) are limiting the growth in air transportation. Thus, increased demand will be satisfied only if there is a good understanding of the magnitude and location of environmental impacts. Models suited to complex interactive systems would help design an air transportation system with improved performance in terms of energy and the environment.

Synergies with National and Homeland Security (9): The DoD uses simulations of complex interactive systems to evaluate battlefield strategy and tactics. Thus, there are potential synergies in terms of using the simulation techniques that the DoD has developed to help evaluate commercial and private operations in the air transportation system. Additionally, the DoD and DHS would be interested in this Challenge because safety is also important for their operations, and the ability to distinguish between a component failure and an attack is predicated on the ability to predict and model failure modes.

Support to Space (3): This Challenge would facilitate space launch operations through civil airspace.

Why NASA?

Supporting Infrastructure (3): NASA has highly capable facilities (such as the Future Flight Central simulator and easily configurable full-motion cockpit simulators that can be integrated with other simulation facilities) that contribute to meeting this Challenge. The DoD, FAA, academia, and industry also have facilities and expertise that would help meet this Challenge.

Mission Alignment (9): This Challenge would directly contribute to the usefulness, performance, speed, safety, and efficiency of aircraft and the air transportation system, and it encompasses the type of long-term research that must occur before industry and operational agencies begin to develop specific components or synthesize components into system prototypes. Thus, this Challenge is well aligned with the NASA mission.

Lack of Alternative Sponsors (3): The capabilities that this Challenge would provide are essential. The DoD is sponsoring related research, but it is not focused on civil aviation applications.

Appropriate Level of Risk (9): This Challenge involves moderate risk.

E2 New concepts and methods of separating, spacing, and sequencing aircraft

Expected growth in the demand for air transportation will require efficient, denser en route and terminal area operations. This necessitates procedures that reduce minimum spacing requirements during all phases of flight and in all weather conditions, through an integrated approach that leverages a suite of emerging technologies such as required navigation performance and automatic dependent surveillance broadcast (ADS-B). The objective of this Challenge is to efficiently accommodate a large number and wide range of aircraft, including UAVs, through spacing and sequencing based on aircraft type and equipment rather than a common worst-case standard. Several concepts of operation should be systematically compared in terms of their technological, business, and human factors issues as well as their impact on capacity, safety, and the environment. This Challenge will study reduced separation operations within the context of existing ATM protocols and revolutionary paradigms that could significantly increase capacity, although the latter would involve a much more complicated transition process.

Integration of UAVs into the air transportation system will require procedures that can safely manage aircraft with diverse performance characteristics and highly automated onboard flight management systems (Sabatini, 2006). Safe, high-capacity operations in a complex future airspace environment will require fundamental research into alternative ATM paradigms such as simultaneous noninterfering operations (Xue and Atkins, 2006) in which general aviation, rotorcraft, and UAV traffic are threaded through airspace unused by commercial air traffic. As onboard automation and cooperative control algorithms are matured (McLain and Beard, 2005), UAV traffic might also be efficiently managed using formations of UAVs that are coordinated locally but treated as a single entity by air traffic controllers and pilots of nearby aircraft. Key milestones include

- Demonstrate high-efficiency airspace and airway structures that can be effectively managed and understood.

- Design and evaluate separation, spacing, and sequencing procedures for UAVs operating in civilian airspace and assess their impact on commercial aircraft capacity and safety.
- Extend models and simulation tools to enable accurate evaluation of emerging technologies (e.g., ADS-B) in all weather conditions and during all phases of flight.
- Complete an in-depth examination of the ability of concepts such as runway-independent aircraft and UAV formations or swarms to safely increase capacity and accommodate nontraditional aircraft operations.
- Demonstrate advanced, autonomous collision avoidance technologies and protocols.

Relevance to Strategic Objectives

Capacity (9): New methods for managing separation, spacing, and sequencing are key enablers to increase capacity in both en route and terminal area airspace.

Safety and Reliability (9): The air transportation system can safely manage growth only through a fundamental understanding of system behaviors and associated constraints. To be certified, new separation, spacing, and sequencing methods and associated procedures must prove they provide levels of safety that are comparable to or better than current operational procedures, even with much higher traffic density.

Efficiency and Performance (9): The current air transportation system operates near saturation, resulting in significant travel delays during periods of increased demand or adverse weather conditions. Alternative spacing and sequencing methods are of paramount importance to alleviate these delays, resulting in more efficient travel despite system growth.

Energy and the Environment (3): New methods to more efficiently space and sequence traffic will have a modest impact on energy use and the environment through reduced holding times and less circuitous flight paths.

Synergies with National and Homeland Security (3): Although primarily directed toward transport operations, new methods for traffic separation, spacing, and sequencing must also take into account surveillance and UAV traffic.

Support to Space (1): Given the relative infrequency of space launches, traffic density is not a factor. Therefore, this Challenge would have little or no relevance to the space program.

Why NASA?

Supporting Infrastructure (3): NASA has established and maintained a research group that studies alternative traffic management concepts in en route and terminal airspace. The FAA and industry also possess relevant expertise and facilities.

Mission Alignment (9): Research associated with this Challenge will greatly benefit the aeronautics community and broaden our fundamental understanding of highly dense flight operations. This Challenge would benefit the air transportation system in general and general aviation in particular.

Lack of Alternative Sponsors (3): NASA has a respected ATM research program capable of pursuing this Challenge. The FAA and private industry also are capable of performing related research—and leveraging work being done in Europe—but it is unclear that sufficient resources will be available from non-NASA sources, especially with regard to the development of revolutionary concepts with long-term application.

Appropriate Level of Risk (9): The development and validation of new methods capable of having a significant impact on capacity will require substantial research, but the goal can be attained with reasonable effort.

E3 Appropriate roles of humans and automated systems for separation assurance, including the feasibility and merits of highly automated separation assurance systems

Air traffic control is currently a labor-intensive process. FAA controllers—aided by radar, weather displays, and procedures—maintain traffic flow and assure separation by communicating instructions to aircraft in their sector of responsibility. Limitations to this traditional paradigm are, in some areas, constraining the capacity of the air transportation system. For example, the FAA required airlines serving the Chicago O Hare airport to reduce some of their flights during 2005 because of congestion-related delays. A recent study of en route sector congestion suggested that capacity could be increased by a factor of two or more while maintaining existing spacing, by developing new systems that merge human and computer decision making and automate time-critical separation assurance tasks (Andrews et al., 2005).

Initiatives to reduce aircraft separation by providing automated advisories to air traffic controllers and flight crews have not lived up to expectations, because of controller workload concerns, institutional resistance, and other factors. The advent of UAVs has caused additional concern because it may not be feasible for UAVs with human-in-the-loop collision avoidance schemes to act in time to prevent midair collisions. This has led to interest in determining whether automating aircraft separation, whereby the controller is neither in the loop nor responsible for separation, is feasible and desirable. However, changing the role of the controller from tactical separation to traffic flow management and trusting automated systems to manage the tactical separation of aircraft would require resolution of major human factors, safety, and institutional issues (Wickens et al., 1998; Woods and Hollnagel, 2006). Collisions could occur if a UAV fails to respond or the automated traffic separation system fails and if human intervention is not effective. This Challenge would determine the appropriate roles of humans and automated systems to assure separation in high-density airspace during nominal and off-nominal operations. As part of this challenge, NASA should assess the feasibility and merits of highly automated separation assurance systems. Key milestones include

- Complete basic research necessary to determine the most appropriate separation assurance roles for humans and automation, for ground-centered and aircraft-centered designs.
- Complete the development of the NASA Ames Advanced Airspace Concept, an automated ground-based separation assurance system, for the en route domain.
- Determine how humans interact with the Advanced Airspace Concept and other automation designs.
- Determine how the Advanced Airspace Concept and other designs respond to air and/or ground automation failures, or when the flight crew fails to respond to automated directives.
- Develop an adaptation of the Advanced Airspace Concept or other designs for UAVs, and determine its performance.
- Determine through analysis and simulation the safety of the Advanced Airspace Concept and other designs.

Relevance to Strategic Objectives

Capacity (9): Recent research indicates that automated separation methods could enable significant en route and terminal capacity growth.

Safety and Reliability (9): The safe use of automated separation must be assured through independent monitoring. Automated separation will reduce traffic delays if it can better adapt to disruptions caused by adverse weather and congestion.

Efficiency and Performance (9): Automated separation could improve system efficiency and performance by reducing spacing requirements.

Energy and the Environment (1): Automation may reduce unnecessary variations in flight times due to holding and thus reduce fuel consumption.

Synergies with National and Homeland Security (3): The advent of automated separation may improve the ability to detect aircraft that deviate from approved flight paths because of terrorist activity or pilot error.

Support to Space (1): This Challenge is likely to have little relevance to the space program.

Why NASA?

Supporting Infrastructure (3): NASA, the FAA, and industry have the facilities and expertise to conduct research on automated separation.

Mission Alignment (9): This Challenge would have a broad benefit for aeronautics in general and civil aviation in particular.

Lack of Alternative Sponsors (3): Research related to this Challenge (by the FAA and foreign research agencies) would likely proceed even without NASA support, though it would be significantly diminished.

Appropriate Level of Risk (9): Developing fully automated separation systems would be very challenging, but a concerted effort is likely to produce worthwhile results and facilitate increases in system capacity and safety.

E4 Affordable new sensors, system technologies, and procedures to improve the prediction and measurement of wake turbulence

Existing wake vortex separation standards reduce system capacity during takeoff and landing operations and instrument approaches. Encounters with a wake vortex are also a growing concern in en route Reduced Vertical Separation Minima (RVSM) airspace (Reynolds and Hansman, 2001).[3]

Current research by the FAA and NASA is focused on procedural enhancements that take advantage of wake transport by winds (Mundra, 2001). For example, the capacity of San Francisco International Airport is expected to improve by using this approach to enable arrivals on both closely spaced parallel runways during low visibility weather. However, the relaxation of in-trail wake separation standards awaits improved measurement and prediction of wake behavior.

Existing sensors and models do not adequately characterize wake decay phenomena, especially at typical final approach altitudes. Improved sensors, including coherent pulsed lidars, capable of directly measuring wake rotational momentum, are needed to support phenomenological studies and enable more accurate predictions of wake magnitude and decay in various atmospheric conditions. Those predictions, combined with models of aircraft upset risk, should allow reduced wake separation standards without degrading safety.

R&T Challenge A10 will conduct research to improve techniques for predicting and measuring the formation, trajectory, and decay of vortices, including methods to accurately predict wingtip vortex formation and define changes in aircraft design to mitigate the strength of the vortices. This Challenge would complement that work by developing affordable new sensors, system technologies, and procedures to improve prediction and measurement of wake strength, location, motion, and aircraft upset risk in terminal and en route airspace. Together, Challenges A10 and E4 will enable safe flight with reduced in-trail wake separation. Key milestones include

[3]Reduced Vertical Separation Minima apply to the airspace from flight levels 290 to 410 (which is equivalent to altitudes of approximately 29,000 feet to 41,000 feet) and create twice as many usable flight levels, decreasing the vertical separation between aircraft from 2,000 to 1,000 feet. While increasing capacity, this also could exacerbate the effects of wake turbulence.

- Demonstrate new sensors, including a scientific, coherent lidar capable of accurate wake velocity strength measurements.
- Conduct phenomenological studies of wake behavior supported by field experiments using ground-based sensor(s) that measure wake decay and atmospheric conditions at altitudes up to 8,000 feet above the ground.
- Determine aircraft upset risks from wake vortices encounters, taking advantage of existing models and enhancing them where needed with field data.
- Demonstrate procedures, monitoring equipment, and other systems to safely reduce wake separation.
- Demonstrate an airborne means to sense and quantify the intensity of hazardous wakes en route in time for aircraft to evade them.

Relevance to Strategic Objectives

Capacity (9): Reduced wake vortex spacing requirements near airports would typically decrease arrival and departure aircraft spacing.

Safety and Reliability (9): Improved wake detection and avoidance systems and procedures will improve the ability to avoid accidents associated with wake vortices, even with higher traffic density.

Efficiency and Performance (3): Aircraft arrival and departure rates will be improved if wake vortex spacing can be safely reduced.

Energy and the Environment (1): Reductions in arrival and departure spacing may reduce airport and airborne congestion and could provide some reduction in fuel burn; however, the amount is difficult to calculate due to the lack of empirical data.

Synergies with National and Homeland Security (1): This Challenge would have little relevance to national and homeland security.

Support to Space (1): This Challenge would have little relevance to the space program.

Why NASA?

Supporting Infrastructure (3): NASA is currently leading a joint program with the FAA in wake vortex procedures and technologies. NASA has also sponsored research in wake upset risks.

Mission Alignment (9): This Challenge would have a broad benefit for aeronautics in general.

Lack of Alternative Sponsors (3): Industry is not supporting wake vortex research because it lacks facilities, and past efforts made little progress. Universities are not engaged due to the high costs of experimentation. Long-term research by NASA is needed to supplement near-term developments being made by the FAA.

Appropriate Level of Risk (9): This Challenge has moderate to high risks. Development of sensors and systems is challenging but doable.

E5 Interfaces that ensure effective information sharing and coordination among ground-based and airborne human and machine agents

The potential for sharing a wide range of information within the air transportation system raises additional questions about how multiple agents (pilots, controllers, other system users, and automated system elements) can coordinate and share information given their disparate viewpoints and contexts. For information sharing to be effective, information must be provided to the right agents, at the right time, and in a fashion that facilitates accurate interpretation regardless of the source of the information. Some of the shared information may be factual (e.g., aircraft position, speed, heading, altitude, and flight plan), while some of it may be less tangible (e.g., potential responses to disruptions). The information elements will also likely vary in their timeliness and accuracy, and access to some information will be restricted for security and business reasons. Developing appropriate interfaces (in terms of information-sharing protocols, as well as display and visualization technology) is a nontrivial challenge, because agents can be easily overwhelmed by too much information or by the need to translate and analyze the information relative to their own situation and goals (Woods et al., 2002). Interfaces for human agents, in particular, will need to include methods for visualizing and interpreting operational situations to facilitate effective judgments and decisions. In addition, information-sharing and decision-making processes will often be conducted collaboratively by multiple agents. Therefore, they will require knowledge of both individual human cognition and of collaborative work among agents with potentially conflicting goals and different representations of the immediate situation (Brennan, 1998; Olson et al., 2001). Information-sharing protocols become exceptionally critical during crises, such as 9/11, when control of the national airspace was transferred to the military. Communications and decision-making protocols were fragmented. Research related to this Challenge must be coordinated with DoD and DHS to avoid a recurrence of such problems. The Challenge should also capitalize on technologies pioneered in the telecommunications industry that would facilitate the transfer of diverse information through dynamically reconfigured networks using thousands of disparate nodes. Key milestones include

- Document improved understanding of human cognitive control, judgment, and decision making in a variety of contexts and under a variety of stressors.
- Document improved understanding of organizational dynamics and business concerns associated with information sharing.

Relevance to Strategic Objectives

Capacity (3): Making it possible for systems agents to share more information and make better use of it will enable the air transportation system to safely handle the expected growth in demand.

Safety and Reliability (9): Effective information sharing is vital, especially during emergencies, when operations are disturbed from established structures and real-time information is central to fluidly developing a course of action involving multiple agents.

Efficiency and Performance (9): Taking better advantage of information sharing will reduce unnecessary flight delays due to uninformed management of system resources and will also allow local entities (e.g., aircraft operators) to make better decisions relative to their individual goals.

Energy and the Environment (1): New methods of information sharing may be required to achieve reduced fuel consumption and more efficient ascent and descent profiles, but overall this Challenge would have only a small impact on energy and the environment.

Synergies with National and Homeland Security (9): This Challenge will facilitate the information sharing in situations involving national and homeland security, and will help manage disparate concerns (e.g., closing airspace for security versus maintaining capacity).

Support to Space (3): This Challenge would facilitate space launch applications through civil airspace and could be of value in the future as the number of U.S. space launches—and U.S. space launch facilities—increases.

Why NASA?

Supporting Infrastructure (3): NASA s Ames and Langley Research Centers have expertise in several human factors areas, although additional insight may be required for the organizational, security, and business aspects of information sharing.

Mission Alignment (9): This Challenge will benefit all segments of the civil aviation community and is consistent with ongoing research at several NASA research centers.

Lack of Alternative Sponsors (3): Industry is not motivated to produce methods and protocols for information sharing beyond some limited applications benefiting themselves (e.g., the Collaborative Decision-Making Program). Some work exists at federally funded research and develop centers (FFRDCs) and the FAA Air Traffic Control System Command Center. The large-scale and interdisciplinary aspects of the research are beyond the scope of most individual university research programs.

Appropriate Level of Risk (9): There is moderate risk due to the scale of the problem and the Challenge of responding to different users with different resources and needs.

E6 Vulnerability analysis as an integral element in the architecture design and simulations of the air transportation system

More than three-fourths of air transportation system delays are weather related (Meyer, 2005). Snow or thunderstorms at major hub airports often significantly reduce overall system capacity and efficiency. Abnormal en route winds cause unexpected peaking and depeaking at arrival gateways. En route convective weather causes disruptive and unpredictable rerouting, precipitating en route delays and reducing capacity and efficiency. Disruptions can also be caused by natural disasters (such as volcanoes, hurricanes, tornadoes, and wildfires), electronic attacks (such as power outages, hurricanes, GPS spoofing, spurious communication messages, and hacking into navigation aids), and physical attacks (such as destruction of control facilities and radars). The effects of these disruptions may be local, regional, or national. In all cases, system capacity and efficiency are directly affected, and, more important, the safety of the air transportation system may be compromised by an inadequate response.

Airlines use a variety of techniques to respond to such disruptions. Some reduce schedule to preposition aircraft for the recovery, when the weather abates; others try to fly their full schedule, hoping that the recovery will take care of itself.

System safety impacts of unplanned service disruptions should be evaluated early in the development cycle of new ATM system architectures, operating concepts, and system components. An agile ATM design should include provisions to counter or recover from system disruptions, and the design of the overall air transportation system should be evaluated by research and simulation to develop both system design concepts and/or operational procedures. In addition, quantitative analyses should be used to assess the safety impact of system architecture options. This Challenge would introduce vulnerability analyses as an integral element in the architecture design and simulations of the air transportation system to reduce the likelihood that the system will experience major system disruptions, to mitigate the severity of specific system disruptions, and to facilitate recovery from system disruptions. The result would be an air transportation system that is self-diagnosing and self-healing. Key milestones include

- Complete end-to-end vulnerability analysis of system architecture and signal flow.
- Demonstrate the ability of a more capable model to simulate critical element disruptions as defined by vulnerability analyses.
- Document safety and capacity impacts using modified system simulations.
- Develop changes in system architecture and operational procedures and demonstrate that they can mitigate the effects of specific system disruptions.

Relevance to Strategic Objectives

Capacity (3): This Challenge would minimize the magnitude, geographic extent, and duration of reductions in system capacity during air transportation system disruptions.

Safety and Reliability (9): Both safety and reliability would be significantly and directly impacted if vulnerability analysis is not included as a basic consideration in system design.

Efficiency and Performance (9): Because of the complex nature of the air transportation system, if sufficient attention is not paid to vulnerability analysis, the overall performance of the system could be excessively degraded in response to weather, major system malfunctions, terrorist actions, etc.

Energy and the Environment (1): Delays and diversions caused by disruptions in the air transportation system would likely have only a short-term effect on energy utilization or the environment.

Synergies with National and Homeland Security (9): Vulnerability analysis would improve the ability of the DoD and DHS to prevent disruptions to the air transportation system and to prepare themselves to respond as effectively and quickly as possible when they do occur.

Support to Space (1): This Challenge would have little relevance to the space program.

Why NASA?

Supporting Infrastructure (3): The NASA Ames air traffic simulation facilities would be an excellent evaluation tool in support of this Challenge. The FAA, DoD, and industry also have relevant facilities and capabilities.

Mission Alignment (9): This Challenge is directly tied to NASA s aeronautics role.

Lack of Alternative Sponsors (3): The FAA, DoD, and DHS also have an interest in vulnerability analysis.

Appropriate Level of Risk (9): Conducting comprehensive vulnerability analyses of the air transportation system would be challenging, but it can be accomplished if adequately supported.

E7 Adaptive ATM techniques to minimize the impact of weather by taking better advantage of improved probabilistic forecasts

Adaptive traffic flow management methods are needed to take advantage of recent improvements in automated aviation weather forecasts. About 70 percent of aviation delay is due to operationally significant weather, including thunderstorms, low ceilings and visibilities, high winds, and turbulence. Exploitation of weather data collected from ground sensors and satellites using advanced image processing and machine intelligence has enabled significant improvements in aviation weather forecasts. One- to two-hour storm motion products are now being routinely displayed in key airport and en route air traffic facilities and in airline dispatch centers. Included are automatically updated estimates of the forecast accuracy, expressed as a probability (Robinson et al., 2004). This information is beginning to be used by air traffic managers and dispatchers, but only manually (Wolfson et al., 2004).

Algorithms are needed that automatically translate the weather forecasts into actionable traffic flow recommendations, with the goal of fully incorporating the weather data into air traffic automation designs. A few examples of automation that translate probabilistic weather forecasts into traffic flow recommendations have been developed, and FAA air traffic managers have shown they can reduce delays. For example, the LaGuardia Airport traffic flow managers are using storm motion forecast tools, such as the Route Advisory Planning Tool, to automatically identify safe departure routes (Evans, 2006). However, many automation systems are not incorporating the new weather information into their designs. This Challenge would demonstrate the use of automated weather forecasts in making traffic flow decisions and determine where this capability is cost beneficial. Key milestones include

- Identify potential reductions in weather-induced delays.
- Demonstrate use of automated weather forecasts in making traffic flow decisions.
- Quantify the benefit of using automated weather forecasts in making traffic flow decisions.
- Determine where this capability is cost beneficial.

Relevance to Strategic Objectives

Capacity (9): Significant benefits from the manual use of new aviation weather forecasts have been realized in isolated cases. ATM operations could make use of advanced weather data to significantly reduce delays.

Safety and Reliability (3): Better integration of improved weather forecasts with air traffic control will reduce flight risks and improve traffic reliability (i.e., on-time performance).

Efficiency and Performance (9): Taking better advantage of improved weather forecasts will reduce unnecessary flight delays due to unnecessary holds on the ground or in the air.

Energy and the Environment (3): With improved weather data, fuel consumption could be reduced through better routing and more efficient climb and descent profiles.

Synergies with National and Homeland Security (1): Improved weather forecasts contribute to enhanced situational awareness and the navigation of intercept aircraft, but overall this Challenge would have a small impact on national and homeland security.

Support to Space (1): This Challenge would have little relevance to the space program; advanced weather forecasts are already providing launch-critical information.

Why NASA?

Supporting Infrastructure (3): NASA has several ATM research programs, but NASA s capabilities are not unique.

Mission Alignment (9): This Challenge would benefit all segments of the civil aviation community and is consistent with ongoing research at several NASA research centers.

Lack of Alternative Sponsors (3): Industry is not developing methods to integrate weather with traffic flow management. Some work exists at FAA-sponsored FFRDCs. Little work is being done at universities, because the necessary test facilities are cost-prohibitive.

Appropriate Level of Risk (9): There is moderate risk due to the scale of the problem and the Challenge of responding to many aviation users with different equipment capabilities and levels of pilot expertise and who respond differently to various kinds of adverse weather.

E8a Transparent and collaborative decision support systems

Air traffic operations are enhanced by effective decision support systems that assist pilots, controllers, traffic flow managers, and airline personnel in tasks such as routing, flight planning, scheduling, and traffic separation. These decision support systems contribute to safe and efficient operations by using technology to enhance human capabilities and collaborate with the operator, as opposed to fully automated systems, which use technology rather than an operator to perform tasks. Collaborative decision support systems are most effective when the operators understand the basis for and limitations in the system s reasoning process and can judge the appropriateness of system-generated recommendations. Similarly, the system s recommendations should take into account operators knowledge and intentions as well as the context in which they operate. Support for reciprocal information sharing and mutual understanding of intentions and actions—a process called grounding—is critical to avoid breakdowns in human–machine collaboration and overall system performance (Sorkin et al., 1988; Lee and Moray, 1994; Smith et al., 2001; McGuirl and Sarter, 2006). This Challenge will identify the type of information to be shared between human operators and automated decision support systems and develop candidate designs for these systems. Key milestones include

- Identify the type of information to be shared between human operators and automated decision support systems and the most appropriate form of information representation and exchange.
- Develop, demonstrate, evaluate, and iteratively refine candidate designs in collaboration with operators.

Relevance to Strategic Objectives

Capacity (3): Collaborative decision support systems will help the air transportation system safely handle the expected growth in demand.

Safety and Reliability (9): Past experience with decision support systems has shown that a lack of transparency can cause users to rely on information provided by decision aids too much or too little, because they do not understand how the decision aids work and what their limitations are. Also, stand-alone systems that perform tasks for, rather than with, human operators have been shown to make it very difficult for operators to monitor their performance and intervene when necessary. Both of these problems can affect safety and can be addressed through improved design of collaborative decision support systems.

Efficiency and Performance (9): Improved system efficiency and performance is a prerequisite for meeting future demands on the air transportation system. Collaborative decision support systems will contribute to this goal by leading to more effective communications, fewer misunderstandings, and more effective operations.

Energy and the Environment (1): More effective and collaborative decision support systems would have only a small impact on energy and the environment.

Synergies with National and Homeland Security (3): National and homeland security would be enhanced by more effective and collaborative decision support systems.

Support to Space (3): This Challenge would facilitate planning and execution of space missions.

Why NASA?

Supporting Infrastructure (3): NASA, especially the Ames and Langley Research Centers, has the resources and expertise to develop improved decision support system designs. NASA is well connected to other organizations conducting research in this field.

Mission Alignment (9): The design of safe and efficient human–machine systems and interfaces is an important part of NASA s aeronautics mission.

Lack of Alternative Sponsors (3): Research associated with this Challenge will likely find a sponsor if NASA does not perform the work. It is not clear, however, that other sponsors are as well qualified.

Appropriate Level of Risk (9): Developing improved collaborative decision support systems is difficult, but NASA has the capability to make substantial progress over current systems.

E8b Using operational and maintenance data to assess leading indicators of safety

Safety analysis is often a reactive, ad hoc process made difficult, in part, by the very high level of safety required of air transportation in the United States. Few unambiguous data points (accidents) are available for analysis, the number of data points continues to decrease because of the success of ongoing safety efforts, and accidents that do occur are increasingly the result of a complex chain of unlikely circumstances, each of them benign (Leiden et al., 2001). While human error is often cited as a major safety concern, successful human performance is also a major (and underreported) contributor to system safety. Thus, a particular concern for safety analysis is the human contribution to safety, especially when predicting the safety impact of dramatic changes to the role of human operators and increased reliance on automation. Likewise, safety analysis must consider individual aircraft as well as systemwide safety, which involves complex interactions among many agents. Using a common set of safety metrics (see R&T Challenge E16), this Challenge would develop methods both for monitoring the current system through ongoing analysis of operational and maintenance data and for predicting potential safety problems associated with proposed changes to the air transportation system. Key milestones include

- Produce a common taxonomy for all safety information acceptable to all stakeholders.
- Demonstrate methodologies to discover and analyze anomalous system, components, and human behavior in nominal and off-nominal conditions.
- Demonstrate methods to integrate system models into analytical processes.
- Demonstrate advanced, affordable methods to analyze anecdotal written reports of safety problems and cross-reference them to operational data from aircraft, ATM, and weather systems.
- Demonstrate methods to cross-reference operational data to certification and training simulator data to determine if aircraft are performing as designers intended and if pilots and controllers are performing as trained.

Relevance to Strategic Objectives

Capacity (3): Safety concerns can pose limits on operating concepts and criteria such as separation standards; however, more effective safety analysis might show that these limits are overly conservative and could be relaxed.

Safety and Reliability (9): Established metrics and methods of assessing and predicting safety issues are fundamental to developing and maintaining safe operations.

Efficiency and Performance (9): Without these developments, efficiency and performance will likely be constrained by overly conservative standards and operational procedures.

Energy and the Environment (1): Methods of ensuring safety should be careful to not conflict with methods of conserving energy and protecting the environment, and vice versa, but overall this Challenge would have only a small impact on energy and the environment.

Synergies with National and Homeland Security (3): Safety concerns can impose limits on unusual types of operations (e.g., UAV operations) within general-use airspace; likewise, in extreme circumstances (e.g., closing the national airspace and grounding all aircraft in an emergency), safe methods are needed to transition between normal and emergency modes of operations, including transfer of operational authority.

Support to Space (3): This Challenge would help improve the safety of the space program.

Why NASA?

Supporting Infrastructure (3): NASA Ames Research Center has expertise in relevant system-safety analysis and monitoring, although additional insight may be required for the organizational, security, and business considerations in safety analysis.

Mission Alignment (9): This Challenge would benefit all segments of the civil aviation community and is consistent with ongoing research at several NASA research centers.

Lack of Alternative Sponsors (3): Industry is not motivated to perform systemwide safety analysis or to share some sensitive data and analyses, which impedes systemwide analyses and the easy sharing of safety-critical information. FAA-sponsored FFRDCs are conducting some related research, but NASA has a unique and objective third-party role given the regulatory function of the FAA. The large-scale and interdisciplinary aspect of the research is beyond the scope of most individual university research programs.

Appropriate Level of Risk (9): There is moderate risk due to the scale of the problem and the difficulty of analyzing many types of operations with different characteristics and technologies.

E8c Interfaces and procedures that support human operators in effective task and attention management

The expected growth in air transportation demand will likely require operators to perform a wider range of tasks and to collaborate more closely with one another and with modern technologies. Pilots may begin to play a more active role in traffic separation or spacing and will need to coordinate their activities and intentions with other pilots and controllers. They will need to interact and exchange information, often interrupting each other and creating new tasks for one another. In general, more information will need to be distributed in a timely manner, task sets will increase, interruptions will become more likely, and the tolerance for delayed action or intervention will probably be reduced. It will be critical to ensure that operators are supported in properly scheduling and prioritizing their tasks, to improve attention management and avoid errors caused by unnecessary task switching, unnecessary interruptions, or inappropriate dismissals of demands (i.e., the failure to switch attention when appropriate and necessary) (Woods, 1995; McFarlane and Latorella, 2002; Ho et al., 2004). Major milestones include

- Complete basic research to document how operators absorb information, process information, and prioritize tasks.

- Demonstrate tools to efficiently evaluate operational data and reports of nominal and off-nominal decision making by operators.
- Demonstrate and evaluate candidate designs and procedures in support of preattentive reference, time-sharing among different tasks, and task switching.[4]

Relevance to Strategic Objectives

Capacity (3): In order to handle the expected growth in demand on the future air transportation system, timely interactions among operators and proper task prioritization will be important

Safety and Reliability (9): Increased task and attention demands on pilots and controllers lead to unwarranted interruptions of ongoing tasks and lines of reasoning. Interruptions are known to increase the risk of errors involving both the interrupted and the interrupting task and should therefore be minimized. At the same time, inappropriate dismissals of demands can similarly affect the safety of operations, especially in congested airspace with reduced separation.

Efficiency and Performance (9): Making sure that operators optimally direct their attention will help avoid errors and breakdowns in coordination that reduce system efficiency and performance.

Energy and the Environment (1): This Challenge has little or no relevance to energy or the environment.

Synergies with National and Homeland Security (3): Attention management challenges faced by DoD and DHS are similar to this Challenge faced by civil aviation. All are engaged in operations that require fast and efficient information exchange and interactions among many stakeholders, and research that will reduce unnecessary disruptions and improve attention management in the civil air transportation system will be of some assistance in addressing these challenges in the DoD and DHS.

Support to Space (3): Some space operations require operators to cope with competing demands for their attention, especially in case of system failures. Thus, this Challenge is relevant to the space program.

Why NASA?

Supporting Infrastructure (3): NASA (especially the Ames and Langley Research Centers) has the resources and expertise to conduct research on improved systems and procedures in support of task and attention management. In fact, limited efforts are already under way to address this growing Challenge.

Mission Alignment (9): Human-centered design and the development of safe and efficient human–machine systems for aviation and space operations are an important part of NASA s mission.

Lack of Alternative Sponsors (3): Research on task and attention management may be conducted by other sponsors if NASA does not address this Challenge. It is not clear, however, that research by others would have a sufficient aeronautical focus.

Appropriate Level of Risk (9): This Challenge faces moderate risk but is likely to lead to significant improvements.

E11 Automated systems and dynamic strategies to facilitate allocation of airspace and airport resources

Many major airports have little or no excess capacity. The competition for airspace and airport resources (e.g., airport departure and arrival slots) at major airports will be exacerbated by growth in commercial and private air travel (including, for example, the introduction of VLJs). Automated systems and dynamic strategies driven by economic reasoning would facilitate quick and effective decision making when the transportation system encounters disruptions. They could also be used during normal operations to quickly negotiate and make decisions regarding, for example, real-time allocation of airspace and landing slots among aircraft with diverse size and performance characteristics, while considering the needs of all stakeholders, air transportation system efficiency, and energy conservation (Cramton et al., 2002). Key milestones include

- Modify available models to create dynamic tools for assessing the current and future state of the air transportation system.
- Document decision-making drivers of all users of the air transportation system.
- Create and demonstrate an architecture to allocate landing slots.
- Create and demonstrate an architecture to allocate airspace dynamically.

Relevance to Strategic Objectives

Capacity (9): Fast-response negotiation, quick decision making, and dynamic strategies that adapt themselves to changing conditions could substantially increase capacity at times and places where air transportation resources are constrained, especially during disruptions.

Safety and Reliability (3): Fast-response decision making will increase safety and reliability during system disruptions.

[4]Preattentive reference is supported by presenting partial information about a potentially interrupting task or event to help the operator decide whether a shift in attention is warranted. The information needs to be presented in such a way that it is quickly noticed and easily processed and understood without requiring an interruption of the ongoing task or line of reasoning (Woods, 1995). Operational systems that provide preattentive reference reduce the risk of task-switching errors and improve operator efficiency and performance.

Efficiency and Performance (9): More effective allocation of access to air transportation resources, including quick response to disruptions in the air transportation resources, will greatly improve system efficiency and performance.

Energy and the Environment (3): Dynamic strategies that lead to more effective allocation of airspace and landing slots would have a positive impact on energy conservation and the environment.

Synergies with National and Homeland Security (3): Quick, highly effective decision-making systems suitable for emergency situations would enhance national and homeland security.

Support to Space (1): This Challenge is not directly relevant to the space program.

Why NASA?

Supporting Infrastructure (3): NASA has the resources to develop decision-making tools, methodologies, and systems based on software agents, and it is well connected to other relevant research communities with relevant skills.

Mission Alignment (9): Improving the performance of the air transportation system is part of NASA s mission.

Lack of Alternative Sponsors (1): The FAA is already supporting research related to traffic flow management and collaborative decision making that would contribute to this Challenge. Current funding is probably not at a high enough level to address all of the complexities of this issue, but in any case, solutions to this Challenge are highly dependent on specific FAA implementation plans and architectures (e.g., the Enhanced Traffic Management System).

Appropriate Level of Risk (9): The technology goals are realistic, and the technical risk is moderate.

E12 Autonomous flight monitoring of manned and unmanned aircraft

Safe, high-capacity operations can only be achieved if pilots (and ground-based operators of UAVs) reliably comply with their communicated intentions. This means that each UAV must have numerous fail-safes in case of system failure or loss of the communications link between a UAV and its operator (Sabatini, 2006).

The effects of unexpected deviations can ripple throughout the system, increasing delays and the risk of collision. An autonomous flight monitoring system would identify unanticipated and unauthorized deviations from flight plans, as well as their likely cause (e.g., degraded equipment performance, adverse weather, or unexpected actions by the pilot or autopilot). The system would also disseminate relevant information to agents in the air transportation system that might be affected, with the goal of rapidly initiating analysis and intervention systems to identify and resolve near- and long-term conflicts or hazards. To be useful, flight monitoring technologies will need to avoid false alarms associated with routine deviations to adjust spacing between aircraft or in response to local weather conditions.

Technologies developed in response to this Challenge could also be used to better predict the near-term consequences of flight plan deviations. Data generated by onboard systems could be combined with data provided by ground systems to extend the time horizon of the predictive capabilities to more than just a few minutes. Key milestones include

- Produce a detailed set of requirements and design specification for flight monitoring systems deployed on manned and unmanned aircraft.
- Demonstrate algorithms and knowledge to enable a flight monitoring system that accurately anticipates, detects, and diagnoses flight plan deviations.
- Demonstrate the ability to more accurately project the near-term results of manipulating aircraft controls and inform pilots of likely consequences in terms of aircraft motion, potential collisions, airspace violations, etc.
- Design protocols for disseminating information from flight monitoring systems locally and throughout the air transportation system.
- Specify corrective actions appropriate for manned and unmanned aircraft in response to unplanned deviations detected by a flight monitoring system.

Relevance to Strategic Objectives

Capacity (3): The ability of an autonomous flight monitoring system to provide early warning of unplanned flight deviations could have a modest impact on capacity by enabling reduced separation standards as a result of increased trust that each aircraft will accurately follow its flight plan.

Safety and Reliability (9): An autonomous flight monitoring system would increase safety by providing information on localized and systemwide deviations and their potential to create hazards or conflicts.

Efficiency and Performance (3): An autonomous flight monitoring system would help assess systemwide performance and delays as well as provide warnings of flight plan deviations, which would allow operators to make changes to improve system performance.

Energy and the Environment (1): An autonomous flight monitoring system would have minimal impact on energy and the environment.

Synergies with National and Homeland Security (9): Early warning of flight plan deviation could help identify potentially hostile action. Autonomous flight monitoring could also provide early indication of tampering with air transportation system equipment (e.g., navigation signals and communication channels).

Support to Space (1): Future space vehicles will have extensive onboard monitoring capabilities, but this Challenge focuses on monitoring of the air transportation system and thus would have minimal direct relevance to the space program.

Why NASA?

Supporting Infrastructure (3): NASA has placed significant emphasis on aircraft and spacecraft diagnostics and monitoring, but it has limited expertise in the systemwide monitoring capabilities associated with this Challenge.

Mission Alignment (9): Autonomous flight monitoring has the potential to significantly enhance aviation safety through improved compliance with flight plans and improved situational awareness.

Lack of Alternative Sponsors (3): Development of a systemwide autonomous flight monitoring capability may also be supported by the FAA, and some capabilities would be supported by commercially developed flight management systems that currently monitor and store statistics onboard each aircraft.

Appropriate Level of Risk (9): Systemwide flight monitoring is feasible, but significant challenges remain to reliably detect, diagnose, and project the impact of flight plan deviations.

E13 Feasibility of deploying an affordable broad-area, precision-navigation capability compatible with international standards

Current Global Positioning System (GPS) satellites do not provide navigation data that are precise enough (particularly with regard to altitude) or reliable enough to support precision approach and landing in low visibility conditions (Shively and Hsaio, 2005). In addition, GPS signals are vulnerable to jamming (Volpe, 2001). Installation of ground-based augmentation systems, such as pseudolites, at each landing area would address these shortcomings. However, ground augmentation, as currently envisioned, is not an affordable solution for many small airports.

In cooperation with the Russian and European sponsors of the Global Navigation Satellite System (GLONASS) and Galileo satellite navigation systems, this Challenge would investigate the feasibility of improving existing systems so that measurement geometry, terrestrial coverage, integration of inertial sources, etc. would provide navigation signals with enough integrity and redundancy to enable a broad-area precision navigation capability without the need for ground-based augmentation or independent backup. Key milestones include

- Demonstrate appropriate concepts of operations.
- Review currently planned enhancements to the GPS, Galileo, and GLONASS systems to assess the degree to which performance improvements and/or design modifications of one or more systems would be required.
- Assess the cost, affordability, and technical feasibility of developing and deploying a fully compliant broad-area precision navigation system, including quality assurance methodologies, based on one or more operational concepts.

Relevance to Strategic Objectives

Capacity (9): A broad-area precision navigation capability (including vertical guidance) would open up any site as a potential landing area and facilitate greater reliance on runway-independent operations. This would increase air transportation system capacity, especially at small airports that currently lack precision approaches.

Safety and Reliability (9): Safety is enhanced with the addition of precision landing guidance in all weather conditions.

Efficiency and Performance (3): Efficiency and performance would be enhanced by the availability of Category III landing at any site.

Energy and the Environment (1): The Challenge would have no significant impact on this Objective.

Synergies with National and Homeland Security (3): A broad-area precision navigation capability would facilitate response to natural disasters or terrorist attacks because it would not depend on preexisting ground infrastructure and it would provide coverage to disaster sites wherever they might be.

Support to Space (1): A broad-area precision navigation capability would be of minimal use to space operations.

Why NASA?

Supporting Infrastructure (3): NASA s space program already has a role in GPS spacecraft design and could help develop requirements and design specifications. The DoD, however, has deployment and operational control of the GPS satellite constellation and the FAA is responsible for certification. Assessing the feasibility of a broad-area precision navigation capability for civil aviation is closely tied to regulatory and economic issues that fall outside NASA s area of expertise.

Mission Alignment (3): The technical feasibility issues are well aligned with NASA s aeronautics mission, but economic feasibility issues are better handled by industry, and regulatory feasibility issues are better handled by the FAA.

Lack of Alternative Sponsors (3): DoD has no requirement to provide a GPS system with these capabilities. Industry is in a good position to assess cost, affordability, and economic feasibility.

Appropriate Level of Risk (9): This Challenge has moderate to high risk.

E14 Advanced spacecraft weather imagery and aircraft data for more accurate forecasts

FAA-sponsored weather research has been successfully exploiting data from the National Weather Service and FAA weather radars, as well as space imagery from Geostationary Operational Environmental Satellites (GOES), to enable accurate 1- to 2-hour forecasts of convective storm motion and other weather hazardous to aviation. These forecasts are beginning to provide significant benefits to civil aviation, especially by reducing delays. More forecast improvements are needed but await better understandings of storm growth and decay phenomena (Wolfson et al., 2004). That, in turn, requires improved space imagery with finer resolution and higher update rates than existing Next Generation Weather Radar (NEXRAD) radars. There is also significant interest in using satellite-based multi- and hyperspectral images to better understand cloud formations and develop precursors to storm growth and decay. New imagery that is expected to provide these data will come with the 2012 launches of the GOES-R satellite and the first satellite for the National Polar-Orbiting Operational Environmental Satellite System (NPOESS). Even so, research is needed to understand how to use these data and combine the knowledge they provide with existing terrestrial sensor data. Key milestones include

- Demonstrate the ability to use existing multi- and hyperspectral space imagery for tactical aviation forecasts using data from the following sources:
  - —Hyperion imager on the Earth Observing-1 Satellite.
  - —Atmospheric Infrared Sounder.
  - —the Infrared Atmospheric Sounding Interferometeron on the Meteorological Operational Satellite (METOP).
  - —Geosynchronous Imaging Fourier Transform Spectrometer developed by Langley Research Center, an on-the-shelf GOES-R prototype sensor that tracks the three-dimensional movement of water vapor and winds, to accelerate the exploitation of GOES-R imagery.
- Demonstrate methods of predicting the growth and decay of convective systems using space imagery and terrestrial data sources on timescales consistent with aviation needs.

Relevance to Strategic Objectives

Capacity (3): Extending the forecast horizon to beyond 2 hours would increase the capacity of the air transportation system during adverse weather.

Safety and Reliability (3): Improvements in the accuracy and reliability of weather forecasts directly impact both safety and dispatch reliability of flight.

Efficiency and Performance (9): Improved weather forecasts will reduce unnecessary flight delays due to excessive ground holds, reroutes, and airborne holding.

Energy and the Environment (3): With improved weather data, reduced fuel consumption and more efficient climb and descent profiles may be achieved.

Synergies with National and Homeland Security (1): Improved weather forecasts contribute to enhanced situational awareness and the navigation of intercept aircraft, but this would be only a small contribution to the overall state of national and homeland security.

Support to Space (1): Advanced weather forecasts are already providing launch-critical information, and improved forecasts would have only a small impact on the space program.

Why NASA?

Supporting Infrastructure (3): NASA is already supporting research in hyperspectral imagery as well as launch and support systems.

Mission Alignment (9): This Challenge would directly benefit the air transportation system, and it would complement ATM research already under way.

Lack of Alternative Sponsors (3): NASA support will ensure that space imagery research already under way includes a component that is specifically focused on tactical forecasts for civil aviation.

Appropriate Level of Risk (9): This Challenge has moderate to high risk.

E15 Technologies to enable refuse-to-crash and emergency autoland systems

Flight management systems can safely execute flight plans from takeoff through landing under nominal conditions, and UAV autopilots are approaching this level of capability. Less well understood is the response of flight management systems to abnormal operating conditions that may occur on the aircraft or in the portion of the air transportation system in which the aircraft is operating. Emergencies may be caused by miscommunications; errors involving onboard or remote pilots, air traffic controllers, or automated systems; and other irregularities (e.g., airframe damage) that significantly impact aircraft performance. Refuse-to-crash systems are intended to prevent both controlled and uncontrolled flight into terrain and collisions with other aircraft (Croft, 2003). Emergency autoland systems would be activated to safely land an aircraft when a failed system makes the aircraft difficult or impossible to continue powered flight safely. Such systems are likely to be most successful if implemented both onboard and on the ground. Key milestones include

- Demonstrate fundamental flight planning and control algorithms for refuse-to-crash and emergency autoland systems applicable to manned and unmanned aircraft.
- Demonstrate robust integration of algorithms within a distributed air transportation system that enables both onboard and remotely controlled recovery from system failures or hostile activities.

- Specify data requirements and protocols that will enable unambiguous local or remote detection of situations that require response by a refuse-to-crash or emergency autoland agent.

Relevance to Strategic Objectives

Capacity (1): This Challenge focuses on safety and has no direct impact on capacity.

Safety and Reliability (9): Successful development of refuse-to-crash and emergency autoland capabilities would provide another layer of safety.

Efficiency and Performance (1): The responsive algorithms developed by this Challenge apply to important but improbable events, so this Challenge would not significantly affect the overall efficiency or performance of the air transportation system.

Energy and the Environment (1): This Challenge has little impact on this Objective.

Synergies with National and Homeland Security (3): An emergency autoland system can enable a damaged or otherwise compromised aircraft to safely land despite reduced performance capabilities.

Support to Space (1): This Challenge would have little impact on the space program.

Why NASA?

Supporting Infrastructure (3): NASA has an active research program on emergency autoland systems but has placed less emphasis on refuse-to-crash systems. This Challenge requires systemwide implementation of these capabilities, which has not been a major focus of NASA or others.

Mission Alignment (9): This Challenge could broadly benefit commercial and general aviation.

Lack of Alternative Sponsors (3): Although other government and industrial organizations would perform some research related to this Challenge, NASA support will be important for the fundamental research required by this Challenge.

Appropriate Level of Risk (9): This Challenge is feasible, but it has a moderate to high risk.

E16 Appropriate metrics to facilitate analysis and design of the current and future air transportation system and operating concepts

As advanced technologies and procedures are developed to address air transportation needs, it is important that their performance be understood and compared to existing capabilities. Metrics are important because the metrics that are used to measure the performance of a system have a direct impact on the design of the system; parameters that are not measured—or are measured incorrectly or incompletely—will not be fully considered or accounted for in the final design. Hence the importance of identifying appropriate metrics and incorporating them into system analysis and design tools and processes. However, there is no comprehensive, widely held set of metrics to analyze and design the current and future air transportation system, assess related operating concepts, and define bounds on system performance. Key milestones include

- Identify and document objective measures of current capacity, safety, and efficiency.
- Conduct sensitivity analyses of the above factors to determine causality.

Relevance to Strategic Objectives

Capacity (3): Additional capacity is a key requirement that any future air transportation system must meet. However, there are many ways to measure capacity, and many places where capacity could be measured. Thus, it is important to develop composite metrics that capture the overall ability of the system to handle traffic.

Safety and Reliability (3): More effective safety and reliability metrics would help guide system changes to improve performance in these areas.

Efficiency and Performance (9): High efficiency is the basis for cost effectiveness. Thus, it is important that the efficiency of a system be known before and during development.

Energy and the Environment (3): Environmental considerations are often considered only at the end of the design process. However, they will impact the acceptance of any proposed changes as evidenced by the litigation surrounding the expansion of airports and changes to terminal area trajectories in the United States. Therefore, such considerations must be measured directly or by proxy (with appropriate metrics) throughout the design process to ensure that the resulting solution is at the very least environmentally feasible.

Synergies with National and Homeland Security (3): The DoD and DHS use many metrics related to security. Metrics that are developed to evaluate the civil air transportation system would be of some interest to the DoD and DHS, in that they would facilitate military operations in civil airspace and improve the ability of the air transportation system to respond to emergencies.

Support to Space (1): This Challenge is not relevant to this Objective.

Why NASA?

Supporting Infrastructure (3): NASA has some researchers who could address this Challenge, but outside expertise would also be needed.

Mission Alignment (9): This Challenge involves long-term research that should occur before others begin to develop specific components or synthesize components into system prototypes. Thus, it is well aligned with NASA s mission.

Lack of Alternative Sponsors (3): This Challenge might be addressed by the FAA if NASA is not able to perform it.

Appropriate Level of Risk (3): This Challenge involves low risk.

E17 Change management techniques applicable to the U.S. air transportation system

The air transportation system comprises technology as well as large organizations with long-standing institutional cultures and business concerns, which must be motivated to participate in new operating concepts. Changing such a complex interactive system is difficult both in terms of the immensity of changing its individual elements (new technologies, personnel training, etc.) and in terms of motivating the institutional and business changes. Additionally, the end state of the future air transportation system remains undefined, so R&T should create and maintain the flexibility to change the system in any of several different directions. This requires the interdisciplinary application of large-scale system engineering, organization design, economics, and financial analysis, which in some ways is beyond the current state of knowledge. Even so, improved change management techniques are vital to a cost-effective, noncontentious, and safe transition to the air transportation system of the future. Key milestones include

- Demonstrate methods to identify key obstacles to change in large-scale sociotechnical systems.
- Demonstrate methods to describe and predict the impacts of proposed changes on personnel roles, skills, and training; staffing levels; organizational structures; operating procedures, policies, and regulations; and economic and financial concerns, including funding sources for government agencies.
- Create an architecture to apply change management methods to interagency work that is developing the Next Generation Air Transportation System.

Relevance to Strategic Objectives

Capacity (9): Many elements of and organizations involved in the air transportation system must collectively and simultaneously transition to new operating concepts to satisfy future demand for air transportation.

Safety and Reliability (9): Poorly executed transitions to new operating concepts may degrade safety due to unclear responsibility and authority, dissonant work practices between and within organizations, and poor use of resources, including newly available information.

Efficiency and Performance (9): Coordinated, simultaneous shifts to new operating concepts will facilitate multiple agents working together to improve the overall performance of the air transportation system. It will also allow individual entities to use their individual resources effectively and efficiently.

Energy and the Environment (1): Improved change management techniques will not have a substantial impact on energy consumption or the environment.

Synergies with National and Homeland Security (3): Poorly executed transitions to new operating concepts may degrade security due to unclear responsibility and authority, dissonant work practices between and within organizations, and poor use of resources.

Support to Space (1): Improved change management techniques developed for the civil air transportation system are unlikely to be of substantial value to the space program.

Why NASA?

Supporting Infrastructure (1): This Challenge would require NASA to acquire additional expertise in large-scale system engineering, organization design, economics, and financial analysis.

Mission Alignment (3): This Challenge would benefit all aeronautics domains, but many aspects of this Challenge involve organizational and economic issues that fall outside the normal scope of NASA s aeronautics research.

Lack of Alternative Sponsors (3): Many other organizations are already involved in transformation of the air transportation system.

Appropriate Level of Risk (3): The risk associated with this Challenge is low if it is properly incorporated into the overall effort to develop the NGATS.

E18 Certifiable information-sharing protocols that enable exchange of contextual information and coordination of intent and activity among automated systems

Situational awareness is required for safe and efficient operation of individual aircraft and the air transportation system as a whole. Numeric data from radar or onboard instruments is routinely processed by onboard flight management systems for navigation and local deconfliction. ATM tools predict conflicts given information on the current status of aircraft and their flight plans. However, these systems are somewhat rigid and do not always adapt well to contingency system disruptions and frequent flight plan alterations.

The air transportation system of the future may use dynamic routing capabilities to increase capacity and efficiency. This would require the system to understand at a more fundamental level aircraft objectives and the protocols by which flight plans will be changed, rather than rely on static flight plans that will likely become obsolete.

Objectives of this Challenge are to (1) model the information that must be shared in a dynamic air transportation system and the criteria under which data must be explicitly communicated rather than inferred and (2) interact with certification authorities to ensure that it will be feasible to transfer research results to operational systems. Research associated with this Challenge should also take into account limitations on the ability to reconfigure aircraft and the time required for each manned or unmanned aircraft to dynamically alter its flight plan, in response to, for example, changes in the environment and the flight plans of other aircraft. Key milestones include

- Quantify communication bottlenecks in the air transportation system during nominal operation and off-nominal operating conditions.
- Define information-sharing protocols that could enable dynamic routing of all classes of manned and unmanned traffic, considering the performance of different aircraft and their ability to respond to flight plan changes.
- Demonstrate the application of strategies to infer the intent of aircraft locally, to minimize the need for high-bandwidth communication across the air transportation communications networks.

Relevance to Strategic Objectives

Capacity (3): Efficient information sharing is a key component of distributed, dynamic routing, but it does not directly increase capacity.

Safety and Reliability (1): This Challenge is explicitly focused on improving the efficiency of the air transportation system.

Efficiency and Performance (9): Information sharing will become a key enabler in a distributed, dynamic air transportation system. This Challenge would directly increase efficiency and performance of the system through minimal and expressive information exchange.

Energy and the Environment (1): Information sharing has no direct impact on energy or the environment.

Synergies with National and Homeland Security (9): Aircraft coordination and interpretation of intent through information sharing have significant overlap with homeland security. Intent inference could enable early detection of compromised aircraft, and managing such deviations will require elements of the air transportation system to be efficiently coordinated.

Support to Space (1): This Challenge is not relevant to this Objective.

Why NASA?

Supporting Infrastructure (3): NASA has participated in the development of information-sharing protocols present in current and emerging ATM systems.

Mission Alignment (9): This Challenge would improve the safety and (indirectly) the capacity of the air transportation system. Effective information-sharing protocols applicable to all aircraft types (e.g., transport, UAV, and general aviation) will help ensure that all aircraft types will be able to function efficiently within the congested airspace of the future.

Lack of Alternative Sponsors (3): Other government and industrial organizations will likely sponsor related work as it applies to transport operations.

Appropriate Level of Risk (3): The technology risk for this Challenge is low.

E19 Provably correct protocols for fault-tolerant aviation communications systems

The future air transportation system will increasingly rely on information exchange and automation. Thus, the ability to communicate among systems (ground- and airborne-based) must be ensured through the application of fault-tolerant system design. Key milestones include

- Demonstrate new communication protocols and design standards that are widely accepted within the aviation community.
- Demonstrate methods for certifying systems that incorporate the new protocols and standards.

Relevance to Strategic Objectives

Capacity (3): Air-to-ground information sharing and new decision support technologies, which will improve capacity, would benefit from reliable communications systems.

Safety and Reliability (9): Fault-tolerant aviation communications systems will enhance the safety and reliability of the air transportation system.

Efficiency and Performance (3): Fault-tolerant aviation communications systems will be more reliable and thus enhance efficiency.

Energy and the Environment (1): This Challenge is not relevant to this Objective.

Synergies with National and Homeland Security (3): Fault-tolerant networks would be better able to withstand equipment failures and deliberate attacks.

Support to Space (1): This Challenge is not relevant to this Objective.

Why NASA?

Supporting Infrastructure (3): NASA has experience designing fault-tolerant systems.

Mission Alignment (3): NASA does not have an explicit mission to develop communication protocols.

Lack of Alternative Sponsors (1): The FAA and industry organizations are able to take on this Challenge.

Appropriate Level of Risk (1): The risk associated with this Challenge is so low that industry or the FAA will likely achieve success even without NASA s involvement.

E20 Comprehensive models and standards for designing and certifying aviation networking and communications systems

The communications technologies being incorporated into new aircraft and integrated airborne and ground systems constitute a major shift from federated systems connected with dedicated wiring to a network-centered approach, where most data are shared on a common data network. A set of overarching models would facilitate the design and certification of network-based air-ground communications systems. These models should be able to accommodate the increasing number of ATM, dispatch, and other functions that are participating in networked communication, as well as increasingly complex protocols. Key milestones include

- Demonstrate independent models of the safety of networked systems.
- Define and document criteria that could be incorporated into standards used for certification of systems.

Relevance to Strategic Objectives

Capacity (3): A defined and consistent approach to certification of aviation networking and communications systems will facilitate development and deployment of aircraft-to-ground ATM communication systems, which will provide more communication channels, improve the ability of the air transportation system to handle large numbers of aircraft in congested areas, and contribute to increased capacity.

Safety and Reliability (9): Comprehensive models and standards for designing and certifying aviation networking and communications systems could make a significant contribution to safety, because future systems that rely heavily on networking and deterministic means of assuring the safety of these systems might not be available. Single failures of a network could affect the performance of multiple aircraft systems. Improved methods may be required to assure that the ad hoc methods currently used will not result in crucial errors going undetected. A side benefit would be improving the consistency and efficiency of certifying network-based systems.

Efficiency and Performance (3): The efficiency and performance of the air transportation system would be improved by communications and networking systems that reduce the need for voice communications between pilots and controllers. However, lack of certifiable approaches may prevent these systems from being implemented. For example, the FAA Aircraft Certification Service originally prohibited the operational use of these systems because there was no assurance that pilots would receive critical information.

Energy and the Environment (1): This Challenge is not relevant to this Objective.

Synergies with National and Homeland Security (1): This Challenge is not relevant to this Objective.

Support to Space (1): This Challenge is not relevant to this Objective.

Why NASA?

Supporting Infrastructure (3): NASA has communications technology experts, it has conducted research in aviation safety, and it has a background in formal methods that might apply to this Challenge. However, communications networking has not been a focus of NASA research.

Mission Alignment (3): This Challenge is not explicitly within the existing NASA mission.

Lack of Alternative Sponsors (1): The FAA and industry organizations could address this Challenge.

Appropriate Level of Risk (1): There is low risk associated with this Challenge.

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F

Lessons Learned from Other Federal Agencies

The statement of task directs the committee to consider lessons learned from the requirements process of the Department of Defense (DoD), from the innovation-driven process used by the Defense Advanced Research Projects Agency (DARPA), and from nonaeronautical research by federal agencies that positively affected areas with strong private sector economic interests. The steering committee did not have time to undertake extensive examinations in these areas, but it did receive presentations from Air Force Headquarters;[1] DARPA;[2] and the Air Force Research Laboratory (AFRL)[3] The committee also reviewed materials on the private sector related to federal research provided to SEMATECH (to support the competitiveness of the U.S. semiconductor industry) and to the Human Genome Project.

SEMATECH was formed in 1987 in response to concerns that the U.S. semiconductor industry was losing market share to international competitors. Initially, 14 high-tech companies, representing 85 percent of the national capacity for semiconductor manufacturing, contributed $100 million. The federal government also established an annual R&D budget of $100 million. Interestingly, DARPA was selected by Congress to be the executive agency for appropriated funds earmarked for SEMATECH. Throughout the 1980s and 1990s, SEMATECH evolved in its role, structure, and orientation in supporting the competitiveness of the U.S. semiconductor industry. It used horizontal and vertical collaboration with industry and government agencies (Carayannis and Alexander, 2004; Spencer and Seidel, 1995).

The steering committee did not determine whether the civil aeronautics industry and the semiconductor industry have enough similarities to justify use of the SEMATECH model for civil aeronautics R&T. However, SEMATECH successfully supported a U.S. industry that was being threatened by foreign competition, as is the U.S. civil aeronautics industry today.

The Human Genome Project is an example of the federal government sponsoring research for the public good. The National Institutes of Health and the Department of Energy brought together international biological and medical research communities in the public and private sectors (Collins et al., 2003; Frazier et al., 2003). Many of the experiences in organizing and managing such a complicated, publicly funded, international effort will be applicable to future large-scale projects in biology. The steering committee did not determine whether these lessons learned would also apply to the civil aeronautics industry. However, the example of federal research funding for the public good is analogous to a great deal of civil aeronautics research, particularly since the government has primary responsibility for providing air traffic control services and also has an interest in improving the efficiency of air transportation to benefit the public and the economy.

DoD s aeronautics R&D is primarily intended to benefit the military services and the defense agencies. The DoD requirements process is derived from a structured dialogue of technology push and mission-requirements pull within the DoD science and technology community, the individual military services, and the unified command user community.

DoD is enhanced by the overlay of the innovation-driven DARPA process. DARPA is organizationally structured to be nimble, and it enjoys certain flexibility and tolerance for risk in expediting prototype demonstrations of fundamental research, cutting-edge discoveries, and new system concepts that have demonstrated some level of success to the science and technology programs of the military services.

[1] Ronald M. Sega, under secretary of the Air Force, "Aerospace science and technology update," Briefing to the steering committee on November 8, 2005.

[2] Anthony J. Tether, director, DARPA, "Bridging the gap," Briefing to the steering committee on November 7, 2005.

[3] Walter F. Jones, director, Plans and Programs, AFRL, "Aeronautics at the Air Force Research Laboratory," Briefing to the steering committee on November 8, 2005.

The DARPA model works, in part because successful research products can be handed off directly to a closely associated user community (the military services). Although the NASA aeronautics program does not enjoy this advantage, DARPA s success implies that NASA should strive to nurture an environment that tolerates risk in aeronautics research, as difficult as that would seem to be given the need for risk aversion when it comes to civil aeronautics, where human life is in the balance. The DARPA experience also presents a model for an aeronautics research strategy that combines technology push and mission-requirements pull, with three caveats:

- The U.S. civil aeronautics industry by nature tends to focus on low-risk (and low-cost) solutions to immediate problems and thus is not an ideal source of requirements for a long-term research program with significant risk tolerance.
- Organizations in the U.S. civil aeronautics community have diverse interests and needs and very rarely speak with one voice on the value of or the requirements for any particular aeronautics R&T project.
- Like NASA, DoD maintains a large institutional base of facilities and a civil service workforce as an integral part of its investment decisions and program formulation. However, DARPA does not and is therefore permitted far more freedom in funding and program decisions.

Thus it is unrealistic to expect that NASA s civil aeronautics program will be able to create the same requirements process and constituency support base that DoD has created, nor will it be able to employ the same innovation-driven model that DARPA has enjoyed. It may, however, be possible to create a virtual requirement process guided by decadal surveys of requirements and priorities.

Likewise, NASA does not have the resources to recreate joint government-industry efforts on the scale of SEMATECH or the Human Genome Project, but those two grand efforts do demonstrate the value of joint undertakings, and NASA may wish to pursue a similar model on whatever scale available resources allow.

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G

Statement of Task and Work Plan

STATEMENT OF TASK

An ad hoc steering committee and supporting panels will be formed under the auspices of the Aeronautics and Space Engineering Board to conduct a study to develop a decadal strategy for federal aeronautics research. The steering committee will provide an overarching roadmap for investment in aeronautics research and technology at NASA. The committee will be supported by five panels, as outlined below.

During the first portion of the study, the steering committee will develop a set of key technical questions, issues, and challenges that federal aeronautics basic and applied research should address over the next 10 years. This broad charge will be the basis for the work of the supporting panels in developing a decadal strategy for national aeronautics. The charge will also identify challenges that will not only have a significant, long-term impact on national aeronautics but that NASA is uniquely suited to address.[1]

As appropriate, the committee will consider the following when laying out its charge to the panels:

- Current plans for national aeronautics research.
- Lessons learned from (1) the requirements process used by the Department of Defense and (2) the innovation-driven process used by the Defense Advanced Research Projects Agency (DARPA) to select, prioritize, plan, and execute its programs.
- Inputs solicited by the committee from government, academia, industry, and other stakeholders in the air transportation community.
- Lessons learned from nonaeronautical research by federal agencies (e.g., the National Institutes of Health) that positively affected areas with strong private sector economic interests.
- The findings of recent studies supported by the federal government and other organizations.

During the second portion of the study, the panels will assess how federal agencies can more effectively answer the key questions, resolve the key issues, and meet the key challenges identified in the first phase. Each panel will be comprised of subject matter experts from the appropriate disciplines and provide the committee with an internal written summary of its results, which will include the following (some topics will not be relevant to the work of all panels):

- Identification of research necessary to further the state of the art in the specific thrust areas identified by the committee.
- A single, prioritized list of goals and objectives in each appropriate technical area suitable for guiding the allocation of federal resources available for national aeronautics research during the next 10 years, including development and maintenance of necessary infrastructure (i.e., research, modeling, simulation, and test facilities); necessary testing and flight demonstrations that will demonstrate the scalability of novel concepts and capabilities to real-world implementation; necessary workforce; and resolution of relevant issues related to safety, security, and the environment.
- Guidance on how federal resources allocated for aeronautics research should be distributed between in-house and out-of-house (academic and industrial) organizations.
- Guidance on how aeronautics research can take advantage of advances in cross-cutting technology funded by federal agencies and private industry.
- Guidance regarding how far along the development and technology readiness spectrum federal agencies should advance key aeronautics technologies.

[1]The result of this portion of the study was a set of six strategic objectives (see Chapter 1) and a modified QFD process, including instructions for defining R&T Challenges and criteria for establishing quantitative scores to prioritize the Challenges (see Chapter 2).

Similarly, the panels will consider the following during their work:

- Worldwide state of the art and state of practice in relevant fields.
- Interdisciplinary research and cross-cutting technologies.
- Systems integration.
- Simulation methods, laboratory and wind tunnel testing, and flight demonstration.
- Special workforce, education, and training issues related to specific areas of expertise.
- Operational requirements of the U.S. air transportation industry, the FAA, airports, the Department of Defense, general aviation, and other users of the national airspace.
- How aeronautics research priorities and endeavors by industry, universities, the Department of Defense (including DARPA), and other government agencies (such as the FAA) should affect aeronautics research by NASA. Areas of particular interest include but are not limited to computational fluid dynamics and turbulence modeling, materials, and networking and information technology.

Based on written internal inputs from the panels, the steering committee will prepare a final report that discusses the framework for current investments and the key issues related to investment in aeronautics R&D, integrates the results of the panels, and provides a set of overall findings and recommendations to provide a cumulative, integrated view of the panel results. The committee will also specifically focus on identifying cross-cutting technologies and broad areas of investment between the various panels recommendations and highlight areas of possible revolutionary advancement. Neither the committee nor the panels will make specific budget recommendations.

WORK PLAN

The study will begin with a joint kick-off meeting between the steering committee and its supporting panels in order to hear directly from NASA and other federal entities the primary purpose of the study. The steering committee of approximately 15 members will develop an overarching set of principles for investment in national aeronautics research and technology and a set of key challenges (technical thrust areas) that will guide the panels work. The supporting panels, as overseen by the steering committee, will individually address the key points in the statement of task, meeting approximately three more times. Each panel will provide an examination of the research priorities, possible research plans, and capabilities necessary to undertake the suggested research. Internal working papers and summaries will be provided to the steering committee from the panels outlining their conclusions, findings, and recommendations. The steering committee will prepare a final report that integrates the results of the panels and provides a cumulative, integrated, and prioritized set of overall findings and recommendations.

It is expected that five supporting panels will be formed (see below) composed of approximately 10 members each:

Panel A: Aerodynamics and aeroacoustics
Panel B: Propulsion and power
Panel C: Materials and structures
Panel D: Dynamics, navigation, and control, and avionics
Panel E: Intelligent and autonomous systems, operations and decision making, human integrated systems, and networking and communications

All five panels should address issues related to subsonic, supersonic, and hypersonic flight regimes; infrastructure; transformation of the air transportation system; workforce; and education. As necessary, one or more subgroups of the steering committee will integrate and evaluate the suggestions of the panels in some or all of these areas.

H

Biographies of Committee and Panel Members

STEERING COMMITTEE

PAUL G. KAMINSKI (NAE), *Chair*, is the chairman and chief executive officer of Technovation, Inc., as well as a senior partner in Global Technology Partners. Dr. Kaminski previously served at DoD as the under secretary of defense for acquisition and technology. His government experience also includes a 20-year career as an officer in the U.S. Air Force, where he directed major development programs, including advanced reconnaissance systems and the stealth program. Dr. Kaminski is a member of the National Academy of Engineering (NAE), a fellow of the Institute for Electrical and Electronics Engineers (IEEE), a fellow of the American Institute of Aeronautics and Astronautics (AIAA), and a senior fellow and past chairman of the Defense Science Board. He received a Ph.D. in aeronautics and astronautics from Stanford University, a B.S. from the Air Force Academy, and M.S. degrees in aeronautics and astronautics and in electrical engineering from the Massachusetts Institutes of Technology (MIT).

WILLIAM W. HOOVER, *Vice Chair*, is currently a consultant for aviation, defense, and energy matters. He is the former executive vice president of the Air Transport Association of America, where he represented the interests of major U.S. airlines, particularly as they relate to technical, safety, and security issues. Before that, he served as the assistant secretary, defense programs, U.S. Department of Energy (DOE), where he was responsible for all aspects of the U.S. nuclear weapons development program. He is also a major general, U.S. Air Force (retired), and had responsible positions in the Air Force Space Program, within NATO, at the Pentagon with the secretary of the Air Force, and in Vietnam, where he commanded a combat air wing and flew 97 missions as a fighter pilot. He has served as chairman of the Aeronautics and Space Engineering Board (ASEB) of the National Research Council and as a member of the NASA Advisory Council. He holds a B.S. in engineering from the U.S. Naval Academy, an M.S. in aeronautical engineering from the Air Force Institute of Technology, and is a distinguished graduate of the National War College and a lifetime national associate of the National Academies.

INDERJIT CHOPRA is the Alfred Gessow Professor in Aerospace Engineering and director of the Alfred Gessow Rotorcraft Center at the University of Maryland (UM), where he acted as department chair from 1988 to 1990 and was the Minta Martin Research Professor from 1996 to 2000. He has been working on various fundamental problems related to the aeromechanics of helicopters, including aeromechanical stability, active vibration control, modeling of composite blades, rotor head health monitoring, aeroelastic optimization, smart structures, micro air vehicles, and comprehensive aeromechanics analyses of bearingless, tilt-rotor, servo-flap, compound, teetering, and circulation control rotors. He has been the principal investigator of four major Army research programs: a university research initiative on smart structures technology; a multidisciplinary university research initiative (MURI) on innovative smart technologies for and actively controlled rotorcraft that rides as smoothly as a jet; the Rotary-Wing Center of Excellence (cosponsored by NASA); and a MURI on micro hovering air vehicles. An author of 150 archival journal papers and 234 conference proceedings papers, Dr. Chopra has been an associate editor of the *Journal of the American Helicopter Society*, the *AIAA Journal of Aircraft*, and the *Journal of Intelligent Materials and Systems* and has served on the editorial advisory boards of *VERTICA*, *Smart Materials and Structures*, *SADHANA*, and *Journal of Aircraft*. He received UM s Distinguished Research Professorship in 1992, UM s Presidential Award for Outstanding Service to the Schools in 1995, the AIAA Structures, Structural Dynamics and Materials Award in 2002, the American Helicopter Society (AHS) Grover E. Bell Award in 2002, the American Society of Mechanical

Engineers (ASME) Adaptive Structures and Material Systems Prize in 2001, the A.J. Clark School of Engineering Faculty Outstanding Research Award in 2002, and the SPIE Smart Structures and Materials Lifetime Achievement Award in 2004. He has been a member of the Army Science Board. He is a fellow of the American Institute of Aeronautics and Astronautics (AIAA), a fellow of the American Helicopter Society (AHS), a fellow of the American Society of Mechanical Engineers (ASME), a fellow of the Aeronautical Society of India (ASI), and a fellow of the National Institute of Aerospace (NIA). He received his Sc.D. from MIT.

EUGENE E. COVERT (NAE) is the T. Wilson Professor of Aeronautics, emeritus, at MIT. His long and distinguished career in aerospace has spanned over 60 years in academia and has included additional stints as chief scientist of the U.S. Air Force, member and chairman of the Air Force Scientific Advisory Board, chairman of the Power and Propulsion panel of NATO s Advisory Group for Aerospace Research and Development, director of the Wright Brothers Facility, and chairman of the ASEB. Dr. Covert s experience provides an important perspective on trends in aeronautical research and development, particularly with regard to propulsion.

ALAN C. ECKBRETH is a private consultant who also serves as the vice president/president-elect of the Connecticut Academy of Science and Engineering (CASE). He has extensive industrial experience in complex reacting flows and previous service to NRC/Air Force Office of Scientific Research (AFOSR) panels and many other government committees. In 2004, he chaired the NRC review panel for NASA s Intelligent Propulsion Systems Foundation Technologies. Dr. Eckbreth earned his doctorate in aerospace and mechanical sciences from Princeton University in 1968. He also holds an M.S. in administrative sciences from Rensselaer. After leaving Princeton, he joined United Technologies Research Center (UTRC) and spent 34 years there in both technical research and senior management positions. Initially, he was engaged in research into the properties of high-power electric-discharge CO_2 convection lasers, but the bulk of his career was spent in developing and applying spatially precise laser techniques for gas dynamic and combustion diagnostic purposes, most notably coherent anti-Stokes Raman spectroscopy. His senior management positions at UTRC included director, Fuel Cells Program; director, Aeromechanical, Chemical, and Fluid Systems Program; and director, Pratt & Whitney Program. Dr. Eckbreth is the author of over 60 technical papers and a book on laser diagnostics and has lectured widely on the subject. He is a fellow of the AIAA and of the Optical Society of America (OSA). He served on the U.S. Air Force Scientific Advisory Board from 1995 to 1999 and on numerous other technical advisory panels to NASA and DoD. In 1985, he received the George Mead Medal from United Technologies Corporation for outstanding engineering achievement. After retiring from UTRC and prior to entering consulting, he held the position of vice president and dean, Rensselaer at Hartford, a branch campus of the Rensselaer Polytechnic Institute (RPI), and was also professor of mechanical engineering in the Department of Engineering and Science.

THOMAS M. HARTMANN is a program manager within the Advanced Development Programs (Skunk Works) organization of Lockheed Martin Aeronautics Company. His primary responsibility is for the quiet supersonic transport (QSST) program and related technology initiatives. He joined Lockheed-California Company as a propulsion engineer in 1980. He has worked on the earliest stages of what is now the F/A-22 Raptor, assuming roles of increasing technical responsibility. In 1992, he was instrumental in the capture of a classified program and transitioned into project management. He has managed several technology and development programs within the Skunk Works. Mr. Hartmann received a B.S. from the University of California, Davis in 1980, with a double major in aeronautical and mechanical engineering. He received an M.S. in aerospace engineering from the University of Southern California in 1984. He has attended several management, executive, and program management development programs within Lockheed Martin and at Defense Acquisition University. In 2002 he was recognized by Lockheed Martin with its NOVA award, the corporation s highest employee recognition award. He holds several U.S. patents related to sonic-boom mitigation technologies and their application to supersonic business jets.

ILAN KROO (NAE) is a professor in Stanford University s Department of Aeronautics and Astronautics. He received his B.S. in physics from Stanford in 1978 and then continued studies at Stanford in aeronautics, receiving a Ph.D. in 1983. He worked in the Advanced Aerodynamic Concepts Branch at NASA Ames Research Center for 4 years before returning to Stanford as a member of the aero/astro faculty. Dr. Kroo s research in aerodynamics and multidisciplinary design optimization includes the study of innovative airplane concepts. He has participated in the design of commercial aircraft, UAVs, sailplanes, America s Cup sailboats, and supersonic aircraft. Dr. Kroo, a member of ASEB, has served as a member of the NRC Committee on Review of the Effectiveness of Air Force Science and Technology Program Changes, the NRC Committee on Breakthrough Technology for Commercial Supersonic Aircraft, and the Committee for Materials, Structures, and Aeronautics for Advanced Uninhabited Air Vehicles. In addition to his research and teaching interests, Dr. Kroo is chief scientist of Desktop Aeronautics, Inc., a software and consulting company.

NANCY G. LEVESON (NAE) is professor of aeronautics and astronautics and professor of engineering systems at MIT. Dr. Leveson conducts research on system safety, software engineering, system engineering, and human–computer interaction. In 1999, she received the Association for Computing Machinery s (ACM s) Allen Newell Award for outstanding computer science research and in 1995 the AIAA Information Systems Award for "developing the field of software safety and for promoting responsible software and system engineering practices where life and property are at stake." This year she received the ACM Sigsoft Outstanding Research Award. She has published over 200 research papers and is author of a book, *Safeware: System Safety and Computers,* published by Addison-Wesley. She has served on numerous National Academies committees.

IVETT A. LEYVA is a senior aerodynamicist at Microcosm, Inc., where she is responsible for the development of ablative chambers and also performs CFD simulations of Microcosm s launch vehicles external aerodynamics. She recently led a testing campaign for a 20k-lbf thrust engine for Microcosm s small launch vehicle for the Defense Advanced Research Projects Agency s (DARPA s) FALCON program. Dr. Leyva worked at the General Electric Global Research Center from 1999 to 2003. There, she worked on pulse detonation engines and led the design, fabrication, and testing of a pulse detonation engine concept at the component and system level. She also initiated and coordinated different research projects with scientists from the former Soviet Union. She has four granted U.S. patents in the area of combustion and four more filed (three of those are also filed in the European Union, Japan, or Canada). Dr. Leyva also worked as a thermal engineer for Exponent, where she investigated the cause, origin, and prevention of aviation accidents as well as fires and explosions on scales ranging from the residential to the industrial. Dr. Leyva graduated from Caltech with a Ph.D. in aeronautics. Her dissertation was a numerical and experimental study on the shock detachment process on cones in hypervelocity flows. Dr. Leyva has been part of several NRC committees for propulsion.

AMY PRITCHETT is the David D. Lewis Associate Professor of Cognitive Engineering in the School of Aerospace Engineering and a joint associate professor in the School of Industrial and Systems Engineering at the Georgia Institute of Technology. Her research encompasses human–automation interaction, including advanced decision aids; procedure design as a mechanism to define and test the operation of complex, multiagent systems (e.g., air traffic control, spacecraft mission control); and simulation of complex systems to assess changes in emergent system behavior in response to implementation of new information technology. She is on the editorial board of the *Journal of Cognitive Engineering and Decision Making*, an area editor of *Transactions of the Society for Computer Simulations*, and associate editor of the *AIAA Journal of Aerospace Computing, Information and Communication*. Her awards include the Jackson Award of the Radio Technical Commission for Aeronautics (RTCA) for contribution to aviation. She previously served on the NRC Committee for Vision 2050 and the NRC committee reviewing the NGATS JPDO plan, where she contributed to the committee s investigation of system modeling and human factors. Dr. Pritchett is currently a member of ASEB.

EDMOND L. SOLIDAY was employed by United Airlines for over 35 years as a pilot, human factors instructor, flight manager, and staff executive, serving the last 11 as vice president for safety, quality assurance, and security. He has served on numerous aviation safety-related advisory boards and commissions, and he chaired the Commercial Aviation Safety Team, the Air Transport Association s (ATA s) Safety Council, the Star Alliance Safety Committee, and the ATA Environmental Committee. Captain Soliday currently serves on the board of governors for the Flight Safety Foundation and on the board for the MIT s Global Airline Industry Program Advisory Group. Among his awards are the Bendix Trophy, the Vanguard Trophy, and the Laura Tabor Barbour International Air Safety Award. Captain Soliday previously served on four NRC study groups.

JOHN VALASEK is director, Flight Simulation Laboratory, and associate professor of aerospace engineering at Texas A&M University. He has been actively conducting flight controls research and configuration design of manned and unmanned air vehicles in both industry and academia for 20 years. His research interests include autonomous intelligent control of unmanned air and ground vehicles, autonomous air refueling, vision-based navigation systems, intelligent cockpit computing and displays, and morphing air vehicles. In industry, he was a flight control engineer for Northrop Corporation s Aircraft Division, where he worked on integrated flight and propulsion control systems in the Flight Controls Research Group and on the AGM-137 tri-services standoff attack missile (TSSAM) in the Flight Controls Analysis Group, where he received the Northrop Corporation Outstanding Contribution to Program Award. He has been an AFOSR summer faculty research fellow for the Flight Dynamics Directorate at Wright Laboratories and a NASA summer faculty researcher in the Guidance and Control Branch at NASA Langley. In addition to university research, he is a consultant on flight control to several companies. He is an associate fellow of the AIAA and a senior member of the IEEE, as well as a chair or member of numerous AIAA and IEEE technical committees. He is a reviewer for the NRC and the AFOSR and a former associate editor for *IEEE Transactions on Education*. He earned a B.S. at California State Polytechnic University and M.S. and Ph.D. degrees from the University of Kansas, all in aerospace engineering.

DAVID VAN WIE is an aerospace engineer in aerospace vehicle design and development, with emphasis on propulsion systems and advanced aerodynamics for supersonic and hypersonic flight vehicles. He has been with the Johns Hopkins University Applied Physics Laboratory since 1983 and is currently a member of the principal professional staff and director of the Precision Engagement Transformation Center. Dr. Van Wie also holds appointments as research professor in the Department of Mechanical Engineering at the Johns Hopkins University and lecturer in the Department of Aerospace Engineering at UM. Dr. Van Wie attended the UM between 1976 and 1986 and received B.S., M.S., and Ph.D. degrees in aerospace engineering. He was also awarded an M.S. in electrical engineering from Johns Hopkins University in 1998. He was awarded the Gene Zara Award for outstanding contributions to the National Aerospace Plane (NASP) program in 1989 and 1992. Dr. Van Wie was a member of the Air Force Scientific Advisory Board s (SAB s) Committee on Hypersonic Air-breathing Vehicles (1991), of the NRC Committee on the Assessment of the Air Force Hypersonic Technology Program (1987), and SAB 2000 summer study on Air Force hypersonics.

ROBERT WHITEHEAD entered government service in 1971 after receiving undergraduate and graduate degrees in engineering mechanics from Virginia Polytechnic Institute and State University and completing a 1-year postdoctoral associateship at the NASA Ames Research Center. Dr. Whitehead began his career with the Department of Navy as a research engineer in the Aviation Department of the David Taylor Naval Ship R&D Center at Carderock. He transferred to the Office of Naval Research (ONR) in 1976 as a scientific officer in applied aerodynamics, managing university and industry research projects. For the next 13 years Dr. Whitehead held a number of positions at ONR, finally as director in the Mechanics Division from 1986 until 1989, when he transferred to NASA Headquarters. Dr. Whitehead began at NASA in the Office of Aeronautics as the assistant director for aeronautics (rotorcraft). He held a variety of other positions, including director of the Subsonic Transportation Division, before becoming the deputy associate administrator for aeronautics in 1994. Dr. Whitehead became associate administrator for aeronautics in 1995 and associate administrator for aeronautics and space transportation technology in 1997. Dr. Whitehead retired from federal service in December 1997. He consulted part-time in the aerospace community and its professional associations, on both a volunteer and a paid basis, until becoming interim president and executive director of the NIA in 2002. With the appointment of a permanent NIA president in October 2003, Dr. Whitehead became NIA vice president for Research and Program Development until June 2004. He currently is a consultant on special projects to NIA.

DIANNE S. WILEY is a Boeing Technical Fellow for Airframe Technology Integration. She serves as the enterprise liaison to the Boeing Technical Fellowship to facilitate technology maturation and technology transition to the space exploration systems business area. In her prior assignment with the Boeing Phantom Works, she was the program manager for airframe technology on the NASA Space Launch Initiative Program, overseeing the development and demonstration of advanced structure and materials technology for next-generation, reusable launch vehicles. Previously, she was with Northrop Grumman for 20 years, where she had been manager of airframe technology. In that position, Dr. Wiley was responsible for research and development and technology transition in structural design and analysis, materials and processes, and manufacturing technology. Dr. Wiley was responsible for developing and implementing innovative structural solutions to ensure the structural integrity of the B-2 aircraft. Dr. Wiley s 25 years of technical experience have involved durability and damage tolerance, advanced composites (organic and ceramic), high-temperature structures, smart structures, low-observable structures, systems engineering, and rapid prototyping. Dr. Wiley holds a Ph.D. in applied mechanics from the University of California-Los Angeles School of Engineering and Applied Science. She attended Defense Systems Management College (1996). She is a graduate of the Center for Creative Leadership (1995), Leadership California Class of 1998, and the Boeing Leadership Center (2002.)

PANEL A: AERODYNAMICS AND ACOUSTICS

DAVID VAN WIE, *Panel Chair* (see biography above).

PAUL BEVILAQUA (NAE) is manager of advanced programs at the Lockheed Martin Aeronautics Company. He joined Lockheed Martin as chief aeronautical scientist of the Lockheed Advanced Aeronautics Company and became chief engineer of advanced development projects in the Lockheed Martin Skunk Works. During this time he played a leading role in creating the Joint Strike Fighter Program and invented the lift fan propulsion system that makes it possible to build variants of a single stealthy, supersonic V/STOL aircraft for the Air Force, Marines, and Navy. Prior to joining Lockheed Martin, he was manager of advanced programs at Rockwell International s Navy aircraft plant. He began his career as a captain in the U.S. Air Force and deputy director of the Energy Conversion Laboratory at Wright Patterson Air Force Base. Dr. Bevilaqua is a member of the NAE and a fellow of the AIAA. He is the recipient of an Air Force Scientific Achievement Award for his contributions to turbulence theory, the AIAA Newbold award for his contributions to V/STOL aircraft technology, the AIAA and SAE aircraft design awards for his contributions to aircraft design, and the Collier Trophy for his lift fan propulsion system. His publications include articles in the *Journal of the AIAA,* the *Journal of the Royal Aeronautical Society,* and the proceedings of many meetings and symposia.

CHARLES BOCCADORO is business area director for Future Strike Systems in the Integrated Systems Western Region, Northrop Grumman, in El Segundo, California. This business area focuses on defining next-generation global attack capability for the Air Force, which currently comprises all Air Force next-generation bomber and related technology studies. His team conducted the DARPA Quiet Supersonic Platform study and shaped sonic boom flight demonstration efforts, which received a 2004 NASA Turning Goals Into Reality Award. His team leads Northrop Grumman s Air Force Next Generation, Long-Range Strike Phase II and Phase III study activities. Previously, he was manager of the aerosciences technology and propulsion advanced design organizations. He has worked for Northrop Grumman since 1980 supporting several air vehicle development programs, including F/A-18E/F, YF-23, and B-2. He is a graduate of MIT and the von Karman Institute for Fluid Dynamics and is an associate fellow of AIAA. He is a patent holder, the recipient of a 2003 *Aviation Week* Laurel, the 2004 AIAA Aircraft Design Award, and the 2005 NASA Vehicle Systems Award.

THOMAS CORKE is the Clark Chair Professor in the Aerospace and Mechanical Engineering Department at the University of Notre Dame. He is also the founding director of the Center for Flow Physics and Control (FlowPAC) and the director of the Hessert Laboratory for Aerospace Research. Dr. Corke is internationally recognized for his research in the areas of fluid instabilities and transition to turbulence, control of turbulent boundary layers, flow visualization techniques, and flow control. He has extensive experimental experience over the full range of Mach numbers, from incompressible to hypersonic flows, in a large number of flow fields, including boundary layers, wakes, and jets. His research also involves computational fluid dynamics especially with regard to acoustic receptivity and plasma actuators. His Ph.D. work on the control of large-scale turbulence in boundary layers for drag reduction led to his receiving a NASA Langley Achievement Award in 1982. He was the first to introduce controlled three-dimensional disturbances to verify subharmonic resonance mechanisms in boundary layers, which was recognized with a NASA Langley Achievement Award in 1995. He was named an associate fellow in AIAA the same year. Dr. Corke wrote the textbook *Design of Aircraft* (Prentice-Hall, 2002), which has to date been adopted by approximately 12 aerospace engineering departments for their capstone design course. He was named a fellow of ASME in 2005.

ILAN KROO (NAE) (see biography above).

ROBERT LIEBECK (NAE) is currently manager of the Blended-Wing-Body Program at Boeing. In his 44 years at Boeing, he has served as program manager on several classified advanced-concept airplane programs, some of which culminated in successful flight vehicles. He has an extensive list of technical publications, and his airfoil work is discussed in several textbooks on aerodynamics. He is also professor of the practice of aeronautics at the Massachusetts Institute of Technology and adjunct professor of mechanical and aerospace engineering at the University of California, Irvine, where he teaches aerodynamics, flight mechanics, and airplane design. He received B.S., M.S., and Ph.D. degrees in aeronautical engineering from the University of Illinois in Urbana Champaign and received the university s College of Engineering Distinguished Alumnus Award in 1996. As a consultant, he designed the wings for racing cars that have won the Indianapolis 500 and Formula 1 races, the keel section for the *America*[3] yacht that won the America s Cup in 1992, and the wing for a World Aerobatic Championship airplane. Dr. Liebeck is a Boeing Senior Technical Fellow, an AIAA fellow, a recipient of the AIAA Aerodynamics Award, a recipient of the AIAA Aircraft Design Award, a recipient of the AIAA Wright Brothers Lectureship in Aeronautics, a fellow of the Royal Aeronautical Society, a recipient of the ASME Spirit of St. Louis Medal, and a member of the NAE.

DAN MARREN is the chief of the Hypersonics Systems Division at the Arnold Engineering Development Center (AEDC). He also serves as the Air Force site director for the AEDC White Oak site in Silver Spring, Maryland, home to the Hypervelocity Wind Tunnel 9. His experience includes technical leadership on over 30 projects relating to advanced hypersonic research and development in the Hypervelocity Wind Tunnel 9 as well as several supersonic projects in Navy supersonic facilities. He had the primary role in the conception, design, and development of a major new facility at White Oak and participated in every other important upgrade to the facility. In his previous experience as ground test coordinator for the Navy reentry special projects office, he managed the ground test program for several Navy programs from the advanced project office. He has chaired panels, studies, and focus groups, providing input as a subject matter expert in hypersonics, and maintains technical positions in the AIAA and the Supersonic Tunnel Association International (STAI). He has designed and taught several short courses on physics, testing, and hypersonics for various audiences, including universities, professional societies, and education and public outreach for younger students. Mr. Marren earned his B.S. in aerospace engineering from the University of Cincinnati and his M.S. in engineering management, specializing in high-temperature gas dynamics, at the University of Maryland.

STEPHEN RUFFIN is an associate professor in the School of Aerospace Engineering at the Georgia Institute of Technology and head of its Aerothermodynamics Research and Technology Laboratory. He leads the computational fluid dynamics (CFD) research thrust and collaborates in its integration with the systems analysis tool and with the aeroelastic analysis. Dr. Ruffin is a specialist in high-temperature gas dynamics, compressible flow aerodynamics, CFD, and airframe-propulsion integration. He is leading the development of a three-dimensional Cartesian-grid-based Navier-Stokes solver for design applications and the development of Cartesian-grid approaches for chemically reacting flows. He has conducted computational and experimental studies of a novel channel concept that provides increased lift/drag ratios for reentry vehicles relative to conventional blunted geometries. Dr. Ruffin is also conducting research on high-speed, high-temperature flows in which vibrational energy modes are substantially excited and in which chemical nonequilibrium exists. He has gained this experience through work in the Thermoscience Division at NASA Ames, NASA Glenn, and during years of high-speed CFD research at the Georgia Institute of Technology, Stanford University (Ph.D., 1993), MIT (M.S., 1987), and Princeton University (B.S.E., 1985).

FREDRIC H. SCHMITZ recently stepped down as the Martin Professor of Rotorcraft Acoustics Research in the Department of Aerospace Engineering at UM and is now working half-time as a senior research professor at UM and is a visiting professor at Stanford University. Dr. Schmitz has 36 years experience in aeronautics, specializing in rotorcraft aeromechanics with an emphasis on rotorcraft acoustics and low-speed aerodynamics. He has received numerous awards and honors for his management accomplishments and his pioneering research. Since 1998, he has been building a new rotorcraft acoustic program at UM that utilizes fundamental experiments to validate key aspects of acoustic theory. His background includes large-scale and model-scale acoustic testing, rotorcraft impulsive noise theory, development of national and international acoustic test facilities, and other contributions to research in acoustics and to research in aeromechanics of low-speed aircraft. He has led both in the development of novel research programs in wind tunnels throughout the world (DNW, The Netherlands, and CEPR-19, France) and in the management of research and operation at the world s largest wind tunnel, the 40 × 80 × 120 foot wind tunnel (NASA Ames Research Center). Before taking early retirement from NASA Ames in 1998, he served NASA as the director of aeronautics, deputy director of information technology, chief of the Applied Aerodynamics Division, and chief of the Full-Scale Aerodynamics Research Division and the U.S. Army as chief of the Fluid Mechanics Division for the Aeroflightdynamics Directorate at the NASA Ames Research Center. Dr. Schmitz has a bachelor s degree in aerospace engineering from RPI and M.S. and Ph.D. degrees from Princeton University. He taught the rotorcraft aeromechanics classes at Stanford University for 18 years while holding positions at NASA and in the Army, achieving the rank of consulting professor. He is a fellow of the AHS and the AIAA, and has a commercial rotary-wing pilot s license.

JOHN SULLIVAN is a professor in the School of Aeronautics and Astronautics at Purdue University. He received a B.S. in 1967 from the University of Rochester and an M.S. (1969) and a Ph.D. (1973) in aeronautical engineering from MIT. After graduation, he cofounded a small high-technology company in California. In 1975, he joined the faculty of Purdue University. His administrative experiences there include director of the Center for Advanced Manufacturing, Codirector of the Product Lifecycle Management Center of Excellence, head of the School of Aeronautics and Astronautics (1993-1998), and associate head (1991-1993) and director of the Aerospace Sciences Laboratory (1983-1995). He directs graduate student research in the general area of experimental aerodynamics/fluid mechanics. He is the author or coauthor of approximately 115 technical publications and has served as the major professor for 40 M.S. and 12 Ph.D. thesis graduate students. He spent a sabbatical year at ONR in 1989-1990 and a year at the Boeing Company in 2002.

KAREN WILLCOX is associate professor of aeronautics and astronautics in the Aerospace Computational Design Laboratory at MIT. She received a bachelor of engineering degree from the University of Auckland in 1994 and M.S. and Ph.D. degrees in aeronautics and astronautics from MIT in 1996 and 2000, respectively. She spent 1 year as a visiting researcher at Boeing Phantom Works in Long Beach, California, working with the blended-wing-body design team. She joined the MIT faculty in the Department of Aeronautics and Astronautics in the fall of 2001. Dr. Willcox s research interests lie in computational simulation and optimization of engineering systems. Her research focuses are firstly in model reduction for large-scale systems, with applications in active flow control, aeroelasticity, and variable-fidelity design methods, and secondly in multidisciplinary system design and optimization, with particular emphasis on economic and environmental factors in aircraft conceptual design.

PANEL B: PROPULSION AND POWER

ALAN C. ECKBRETH, *Panel Chair* (see biography above).

ROBERT J. BAKOS is the vice president and general manager of ATK GASL. He is responsible for the overall management of the ATK GASL business unit in advanced aeropropulsion and hypersonic technology development. Previously, he has been the vice president of engineering for Allied Aerospace, the vice president of research and development for GASL, and the director of the HYPULSE Laboratory at GASL. Dr. Bakos is the author of over 30 conference and journal papers on the development of hypersonic technologies and test techniques. He is a senior member of the AIAA and serves on the AIAA HyTASP Program Committee. He received his B.S. in civil engineering from Polytechnic University and his M.S. and Ph.D. in mechanical engineering from Cornell University and the University of Queensland, respectively.

MEYER J. "MIKE" BENZAKEIN (NAE) has experience in both industry and academia. Currently the chair of the Department of Aerospace Engineering at the Ohio State University, he has over 37 years of experience with GE Aircraft Engines (GEAE) as the general manager of advanced engineering, where he was responsible for technology maturation and for strengthening the linkage between the preliminary design of engine systems and production hardware design. In a previous assignment, Dr. Benzakein was general manager for engine systems design and integration, where he was responsible for engineering leadership and technical oversight of commercial and military aircraft engine programs. He is a fellow of the AIAA, a fellow of the Royal Aeronautical Society, and was a member of two NRC committees. He was nominated to the NAE for achievements in international technical cooperation and propulsion engine technology. Dr. Benzakein has experience in the design and production process, as well as expertise in engineering materials, noise and emissions, and systems engineering.

JAMES L. BETTNER retired from Rolls-Royce Aero Engines in 2002, where he was the Program Manager for the AE 3007H engine, which is the propulsion system for the Air Force s high-altitude, long-endurance Global Hawk unmanned aerial vehicle. Previously, he was the supervisor of the Preliminary Design Department, where he conducted studies on material properties in advanced engines, convertible engines, gearboxes for high-speed rotorcraft, wave rotors, and fuel-cooled engines. Dr. Bettner also directed ERAST studies of optimum propulsion systems for very-high-altitude research aircraft. He directed the preliminary design of a propulsion system for a large fan-in-wing Special Operations Force aircraft, where the engines powered a conventional fan in forward flight but were clutched to the fan-in-wing for vertical takeoff and landing. He directed the preliminary design analysis of developing a 2000-pound-thrust turbofan from the T800 turboshaft engine for a medium-altitude application. Prior to that, Dr. Bettner was a member of the propfan development team, which included the NASA-funded single-rotation propfan test assessment (PTA) and the company-funded counter-rotation PW-Allison 578 projects. He received his Ph.D. from Purdue University. Dr. Bettner has expertise in engine materials, propfans, and other elements of propulsion.

DAVID "ED" CROW (NAE) graduated from the University of Missouri-Rolla with a Ph.D. in mechanical engineering. He joined the faculty of the University of Connecticut as a distinguished professor in residence in the mechanical engineering department after a distinguished career in industry. Dr. Crow joined Pratt & Whitney in 1966, rising to the position of senior vice president of Pratt & Whitney s engineering organization in May 1997, where he was responsible for the design, development, validation, and certification of all Pratt & Whitney large commercial engines, military engines, and rocket products. He also led the research and development of advanced technologies systems to meet future aircraft requirements. Dr. Crow previously held the position of senior vice president for Pratt & Whitney s large commercial engines organization, which included the PW4000 and JT9D high-thrust family of products. He is a past secretary of the Society of Automotive Engineers (SAE) and a member of both ASME and AIAA. In addition to having served as past president of Pi Tau Sigma, he has served on the Engineering Advisory Board at Clarkson University and is an elected member of the University of Missouri-Rolla Academy of Mechanical Engineers. He was named a member of the NAE in 1998. Dr. Crow has expertise in propulsion engineering, thermodynamics, aerodynamics, systems engineering, and rocket propulsion engineering.

MEHRDAD (MARK) EHSANI is Robert M. Kennedy Professor in the Department of Electrical Engineering at Texas A&M University. He is the director of the Power Electronics and Motor Drives Laboratory, the Advanced Vehicle Systems Research Program, and the Texas Applied Power Electronics Consortium (TAPC). Previously, he held positions at the University of Texas Fusion Research Center and at Argonne National Laboratory. Dr. Ehsani is a professional engineer, an IEEE fellow, an SAE fellow, and chairman of the IEEE Vehicular Technology Society s Vehicle Power and Propulsion Committee. He is the author of over 300 publications, 12 books, and over 23 patents. He has won numerous awards for engineering and teaching, including the IEEE Vehicular Technology Society 2001 Avant Garde Award, the BP Amoco Faculty Award for Teaching Excellence in the College of Engineering, and the IEEE Undergraduate Teaching Field Award. He served on the NRC Committee on Assessment of Combat Hybrid Power Systems and the Review of Proposals for NASA s Low Emissions Alternative Power (LEAP) project. He received a B.S. and an M.S. in electrical engineering from the University of Texas at Austin and a Ph.D. from the University of Wisconsin-Madison. Dr. Ehsani has expertise in power electronics, motor drives, vehicle power and propulsion systems, and hybrid vehicles and their control systems.

JEFFREY W. HAMSTRA graduated from the University of Michigan with an M.S. in aerospace engineering. Mr. Hamstra is a Lockheed Martin fellow in propulsion integration at Lockheed Martin Aeronautics Company in Fort Worth, Texas, and is currently assigned to the F-35 Joint Strike Fighter Vehicle Systems team. He has 21 years of experience in jet propulsion systems integration, including program experience from the F/A-22, F-16, and Skunk Works advanced development programs. He has performed as a research and development principal investigator, aircraft project lead, and Propulsion Department manager. He is an associate fellow of the AIAA and deputy director of the AIAA Propulsion and Energy Group. He was inducted as a Lockheed Martin fellow in 2003. He is familiar with the U.S. aircraft engine industry, government propulsion organizations, and propulsion technology development programs and has expertise in propulsion engineering and propulsion systems integration.

IVETT A. LEYVA (see biography above).

TIMOTHY LIEUWEN is an associate professor at the Georgia Institute of Technology. He received his B.S. (1995) from Calvin College and his M.S. (1997) and Ph.D. (1999) from the Georgia Institute of Technology. Dr. Lieuwen is the author of two book chapters, 30 refereed journal articles, and over 100 conference publications. He holds four patents and is an associate editor of the *Journal of Propulsion and Power*. He has consulted with many of the major gas turbine manufacturers. Dr. Lieuwen has held various leadership roles on the Air Breathing Propulsion technical committee of AIAA and the Combustion and Fuels Committee of ASME. Dr. Lieuwen has served on the organizing committees of several major international conferences sponsored by both AIAA and ASME. Dr. Lieuwen s awards include the National Science Foundation s CAREER Award, the AIAA Lawrence Sperry Award, and the ASME/International Gas Turbine Institute (GTI) Turbo Expo Best Paper Award. Dr. Lieuwen has expertise in acoustics, combustion, and stability.

LOURDES QUINTANA MAURICE is the chief scientific and technical advisor for environment in the Federal Aviation Administration s Office of Environment and Energy. She serves as the agency technical expert for basic and exploratory research and advanced technology development focused on aircraft environmental impacts and its application to noise and emissions certification. She previously served as the Air Force Deputy, Basic Research Sciences and Propulsion Science and Technology, in the office of the Deputy Associate Secretary of the Air Force for Science and Technology. She also worked at the Air Force Research Laboratory s Propulsion and Power Directorate from 1983 to 1999, planning and executing basic, exploratory, and advanced development propulsion science and technology programs, focusing on state-of-the-art aviation fuels and propulsion systems. Her areas of expertise include pollutant formation chemistry, combustion kinetics, hypersonic propulsion, and aviation fuels. She received a B.Sc. in chemical engineering and an M.Sc. in aerospace engineering from the University of Dayton in Dayton, Ohio, and a Ph.D. in mechanical engineering from the University of London s Imperial College at London, United Kingdom. She is also a distinguished graduate of National Defense University s Industrial College of the Armed Forces, where she earned an M.Sc. in national resource strategy. Dr. Maurice has served as an advisor to the United Nations Intergovernmental Panel on Climate Change. She has served on numerous NRC committees, and on the AIAA s Propellants and Combustion Technical Committee and as the U.S. chair for the AIAA/International Council of Aeronautical Sciences (ICAS s) International Conference in Celebration of the Centennial of Flight. Dr. Maurice is an associate editor for AIAA s *Journal of Propulsion and Power* and serves on the editorial board of the *International Journal of Aeroacoustics*. She has authored over 90 publications and is a 2003 fellow of AIAA.

JAMES C. McDANIEL, JR., is a professor of mechanical and aerospace engineering at the University of Virginia. He is a member of a number of professional societies, including the AIAA, the American Physical Society (Division of Fluid Dynamics), the OSA, and the Combustion Institute of America. He has served on the AIAA Aerodynamic Measurements Technical Committee and currently serves on the AIAA National Aircraft Design Technical Committee and the National SCRAMJET Testing Standards Committee. He has consulted for numerous companies, including Grumman Aircraft, General Electric, Rocketdyne, and Pratt & Whitney. He received a NASP Distinguished Service Award, several aerospace teaching awards, and has advised numerous competition-winning student aircraft design teams. Dr. McDaniel s research interests include fluid mechanics, combustion, laser-based flowfield measurements, and aircraft design. He is the director of the Aerospace Research Laboratory, where basic research in high-speed fuel/air mixing and combustion is conducted using laser-induced fluorescence and other nonintrusive optical measurement techniques. He received a B.S. in aerospace engineering from the University of Virginia as well as an M.S. in electrical engineering and an M.S. and a Ph.D. in aeronautics and astronautics from Stanford. He was also an active-duty pilot in the Air Force and holds commercial, multiengine pilot ratings. Dr. McDaniel has expertise in experimental high-speed propulsion.

TRESA M. POLLOCK (NAE) is the L.H. and F.E. Van Vlack Professor of Materials Science and Engineering at the University of Michigan, Ann Arbor. She received a B.S. from Purdue University in 1984 and a Ph.D. from MIT in 1989. Dr. Pollock was employed at General Electric Aircraft Engines from 1989 to 1991, where she conducted research and development on high-temperature alloys for aircraft turbine engines. She was a professor in the Department of Materials Science and Engineering at Carnegie Mellon University from 1991 to 1999. Her research interests are in the processing and properties of high-temperature structural materials, including nickel-base alloys, intermetallics, coatings, and composites. Professor Pollock is president of The Minerals, Metals and Materials Society (TMS) and associate editor of *Metallurgical and Materials Transactions*. She is a fellow of ASM International and has received the ASM International Research Silver Medal Award. Dr. Pollock was elected to the NAE in 2005. She also served on the NRC s Committee on Material Science and Engineering: Forging Stronger Links to Users. She has expertise in materials for propulsion applications.

WILLIAM TUMAS is a program manager for the Office of Energy and Environment Initiatives at Los Alamos National Laboratory (LANL) as well as director of the Los Alamos Institute for Hydrogen and Fuel Cell Research. He is the lead principal investigator and coordinator of the DOE Center of Excellence for Chemical Hydrogen Storage, which comprises seven universities, four companies, and two national laboratories, including LANL. Prior to joining Los Alamos in 1993, Dr. Tumas was a research chemist, then a project leader in environmental and oxidation catalysis at DuPont Central Research. He was also a member of the DuPont Corporate Catalysis Center and the Corporate Environmental Technology Panel. Dr. Tumas received his B.A. in chemistry summa cum laude from Ithaca College in 1980. He received his Ph.D. in organic chemistry from Stanford University in 1985 as a National Science Foundation (NSF) graduate fellow and a Hertz Foundation fellow, where he studied the dynamics and reaction mechanisms of gas-phase negative ions. He carried out postdoctoral research in organometallic chemistry at the California Institute of Technology from 1985 to 1987 under a National Institutes of Health (NIH)/ Chaim Weizmann postdoctoral fellowship. Dr. Tumas s research activities have included chemical hydrogen storage; homogeneous and phase-separable catalysis; catalytic transformations and chemical processing in supercritical fluids and alternate reaction media; green chemistry; and waste treatment technology development and assessment. He is the coeditor of the book *Green Chemistry Using Liquid and Supercritical Carbon Dioxide*. He has over 45 peer-reviewed publications and has given over 40 invited presentations, including invited talks at seven different Gordon Research Conferences. He chaired the 1998 Gordon Conference on Green Chemistry. Dr. Tumas is also the president of Big Rock Consulting, LLC, through which he has carried out technology assessment for the U.S. Army and Science Applications International Corporation (SAIC) for over 4 years. He was also a founding board member of the Green Chemistry Institute (1997-2002), which is now part of the American Chemical Society. He participated on three NRC committees, including 5 years on the Committee on Review and Evaluation of the Army Chemical Stockpile Disposal Program, where he contributed to 10 NRC reports. He has expertise in fuel cells and hydrogen power.

PANEL C: STRUCTURES AND MATERIALS

DIANNE S. WILEY, *Panel Chair* (see biography above).

SATYA N. ATLURI (NAE) is the Samueli/von Karman Chair in Aerospace Engineering at the University of California, Irvine. Previously, he was the Hightower Chair in Engineering at Georgia Tech and the Jerome Clarke Hunsaker Professor of Aeronautics at MIT. He is a member of the NAE, a distinguished alumnus of the Indian Institute of Science, a fellow of the Third World Academy of Sciences, a member of the European Academy of Sciences, a foreign fellow of the Indian National Academy of Engineering, an honorary fellow of the International Congress on Fracture, and a fellow of several learned societies, including the American Academy of Mechanics, AIAA, the Aeronautical Society of India, ASME, the U.S. ACM, and the International Association for Computational Mechanics (IACM). He is also the recipient of numerous awards, including the Hilbert Medal, the National Medal of Technology Citation for Distinguished Service, the FAA Excellence in Aviation Award, the Pendray Aerospace Literature Award, and the A.C. Eringen Medal. He has chaired committees for the National Academy of Engineering, the USA-India Science and Technology Forum, and the U.S. Army, as well as numerous technical conferences. He is the editor of a number of journals, including *Computer Modeling in Engineering and Sciences*, which he also founded. His research includes computational modeling in multidisciplinary engineering and the sciences; structural integrity and damage tolerance of rotorcraft; meshless methods of computational sciences, especially the meshless local Petrov-Galerkin (MLPG) and the meshless local boundary integral equation (LBIE) methods that he and his students recently pioneered; computational nanoengineering and science; wireless virtual airport for enhanced aviation security; device modeling in microelectromechanical systems; and aging and life-enhancement of aircraft, spacecraft, and power-generating systems. He has performed research for the U.S. Rotorcraft Industry Technology Association, the NSF, ONR, AFOSR, the Army Research Office, the Nuclear Regulatory Commission, NASA, and many others, including directing major research efforts such as the FAA-sponsored National Center of Excellence for Aging Aircraft and the SAFPAS remote airport project at UCLA.

GREGORY CARMAN is professor of mechanical and aerospace engineering at UCLA, having been at the university since 1992. He is also head of the Active Materials Laboratory, where research is performed in shape memory alloys, piezoelectric materials, and fiber-optic sensors, focusing on developing and understanding the combined electromagnetothermomechanical response to these active materials. Dr. Carman is a fellow of the ASME, serving in leadership roles within the Adaptive Structures and Materials Systems Committee of the Aerospace Division. He serves on the editorial advisory board of the *Journal of Composite Materials* and has served in various editorial roles on many other materials journals. Dr. Carman is associate editor on the *Journal of Intelligent Material Systems and Structures*. He was awarded ASME s Adaptive Structures and Material Systems Prize in 2004 and was an invited lecturer at the NAE s Annual Frontiers Symposium in 2004. Dr. Carman has spent several summers performing research at government laboratories, including the Jet Propulsion Laboratory and the AFOSR at Wright Patterson Air Force Base. He received a Ph.D. in engineering mechanics from Virginia Polytechnic Instititute, an M.S. in metallurgical and materials engineering from the University of Alabama, and a B.S. in engineering science and mechanics from Virginia Polytechnic Institute. Dr. Carman has prior experience in proposal review for the AFOSR, NSF, and Hong Kong Science Foundation.

INDERJIT CHOPRA (see biography above).

JANET DAVIS is manager of the Composite Structures Department at the Rockwell Scientific Company and has more than 15 years of research experience in materials science. Prior to joining Rockwell Scientific in 1996, she held positions at Lawrence Livermore National Laboratory (LLNL) and Cambridge University. Her work has focused on strengthening, toughening, and improving the reliability of advanced materials, especially fiber-reinforced composites and structural ceramics. Her current responsibility is to guide a team of research scientists to develop advanced ceramics and composites, with an emphasis on microstructure and property relationships and robust processing methods. Dr. Davis has extensive experience in ceramic powder processing, composite fabrication, mechanical properties evaluation, and microstructural analysis. She obtained a B.S. in ceramic engineering from the Ohio State University and a Ph.D. (1993) in materials engineering from the University of California at Santa Barbara, and has authored or coauthored more than 30 research publications and two patents.

RAVI B. DEO is responsible for space research and technology programs at Northrop Grumman Integrated Systems. During his 27 years at Northrop Grumman, he has been a program and functional manager for government- and company-sponsored projects on cryotanks, integrated system health management, aerospace structures, materials, subsystems, avionics, thermal protection systems, and software development. He has extensive experience in roadmapping technologies, program planning, technical program execution, scheduling, budgeting, proposal preparation, and business management of significant technology development contracts. Among his significant accomplishments are the NASA-funded Space Launch Initiative (SLI), Next-Generation Launch Technology (NGLT), the Orbital Space Plane (OSP), and high-speed research (HSR) programs, where he was responsible for the development of multidisciplinary technologies. Dr. Deo has over 50 technical publications and is the editor of one book. He holds a B.S. in aeronautical engineering from the Indian Institute of Technology in Bombay and M.S. and Ph.D. degrees in aerospace engineering from the Georgia Institute of Technology.

PRABHAT HAJELA is a professor of mechanical, aerospace, and nuclear engineering at RPI. Current research interests include analysis and design optimization of multidisciplinary systems; system reliability; emergent computing paradigms for design; artificial intelligence; and machine learning in multidisciplinary analysis and design. Dr. Hajela recently completed a year as an ASME congressional fellow in the office of Senator Conrad Burns, advising on technology policy. Before joining RPI, he was on the faculty at the University of Florida for 7 years. Dr. Hajela is a fellow of the AIAA, the Aeronautical Society of India, and the ASME, and he is vice president of the International Society of Structural and Multidisciplinary Optimization. He has served on the Multidisciplinary Design Optimization Technical Committee of the AIAA and the executive committee for the ASME Aerospace Division (chair, 2001-2002) and was chair of the Division s Technical Committee on Structures and Materials (1999-2002). He is the editor of *Evolutionary Optimization*, has served as an associate editor of the *AIAA Journal*, and is on the editorial board of six other international journals. He has published over 255 papers and articles in the areas of structural and multidisciplinary optimization and is an author or coauthor of four books in these areas. Dr. Hajela has an M.S. and a Ph.D. in aeronautics and astronautics from Stanford University and a B.Tech in aeronautical engineering from IIT at Kanpur, India. He has not previously served on an NRC committee.

MARK K. HINDERS holds B.S., M.S., and Ph.D. degrees in aerospace and mechanical engineering from Boston University and is currently a professor of applied science at the College of William and Mary in Virginia. Before coming to Williamsburg in 1993, Dr. Hinders was senior scientist at Massachusetts Technological Laboratory, Inc., and a research assistant professor at Boston University. Previously, Dr. Hinders was an electromagnetics research engineer at the Air Force Rome Laboratory located at Hanscom Air Force Base. He conducts research in wave propagation and scattering phenomena applied to medical imaging, intelligent robotics, security screening, remote sensing, and nondestructive evaluation. Dr. Hinders has not previously served on an NRC committee.

ROBERT SCHAFRIK is currently the general manager of the Materials and Process Engineering Department at GE Aircraft Engines. He is responsible for developing advanced materials and processes used in GE s aeronautical turbine engines and their marine and industrial derivatives. He oversees materials application engineering activities supporting GEAE s global design engineering, manufacturing, and field support activities. He also operates a state-of-the-art in-house laboratory for advanced materials development, characterization, and failure analysis. Prior to joining GE in November 1997, he served in two concurrent positions at the NRC (the operating arm of the National Academy of Sciences and the NAE), which he joined in 1991: director, National Materials Advisory Board, and director, Board on Manufacturing and Engineering Design. Under his direction, 33 final reports for studies were issued that addressed significant national issues in materials and manufacturing. Dr. Schafrik also served in the U.S. Air Force in a variety of capacities and retired as a lieutenant colonel. He has a Ph.D. in metallurgical engineering from Ohio State University, an M.S. in information systems from George Mason University, an M.S. in aerospace engineering from the Air Force Institute of Technology, and a B.S. in metallurgy from Case Western Reserve University.

NANCY R. SOTTOS is a professor in the Department of Theoretical and Applied Mechanics and the Beckman Institute for Advanced Science and Technology at the University of Illinois at Urbana-Champaign. Her research interests include the mechanics of complex heterogeneous materials (advanced composites, thin-film devices, smart materials); mesoscale characterization; and autonomic materials systems. Her work at the Beckman Institute addresses issues in the development of autonomic materials systems that have the ability to adapt and respond in an independent and automatic fashion. Dr. Sottos s research group is investigating new experimental methods to quantify autonomic response (e.g., the healing efficiency of a self-healing polymer) and understand this response in terms of the materials chemistry, processing, and microstructure. Dr. Sottos began her career at the University of Illinois in 1991, serving as an assistant professor. In 1997 she became an associate professor, in 1998 she served a 1-year rotating term as assistant dean of engineering, and in 2002 she was promoted to full professor. In 2005, she was named the Donald Biggar Willett Professor of Engineering. She serves as an editorial board member for the *Composites Science and Technology* journal, as senior technical editor of *Experimental Mechanics*, and as a technical reviewer for multiple technical journals. Dr. Sottos received a B.S. and a Ph.D. in mechanical engineering from the University of Delaware. She also serves as the faculty advisor for the Student Chapter of the Society of Women Engineers and as national student chapter coordinator for the Society of Engineering Science.

GREGORY WASHINGTON holds the rank of professor of mechanical engineering at the Ohio State University (OSU). He is also the associate dean of research for the College of Engineering at OSU. Dr. Washington has been involved in multidomain research for the last 12 years. His core area of interest is dynamic systems, with an emphasis on modeling and control of smart material systems and devices. During this time he has been involved in the following applications: the design and control of mechanically actuated antennas, the design and control of advanced automotive systems incorporating smart materials, the design and control of hybrid electric vehicles, and structural position and vibration control with smart materials. He is presently working on ultralightweight, structurally active antennae and sensory systems that involve the use of smart materials. His specific area of research lies in the modeling and control of novel systems and devices that incorporate smart materials. He is the author of more than 100 technical publications in journals, edited volumes, and conference proceedings. He is a technical reviewer for ASME, AIAA, and IEEE journals, as well as the NSF. He participated in the 2004 NAE *Frontiers in Engineering* and the Defense Sciences Study Group. He has received multiple research and teaching awards. He received B.S., M.S., and Ph.D. degrees from North Carolina State University.

TERRENCE A. WEISSHAAR is professor of aeronautics and astronautics at Purdue University and is currently a program manager at DARPA. Dr. Weisshaar s research areas center on aircraft design, structural optimization processes, and integration of aerospace technologies into vehicle conceptual and preliminary design. His past research contributions include development of aeroelastic design tailoring with advanced composite materials, and studies that assisted in the development of the DARPA X-29 research aircraft. He led fundamental aeroelastic research efforts for aircraft configurations such as the oblique-wing supersonic aircraft, the X-wing stopped rotor, and the joined-wing Sensorcraft. In addition, over the past decade, he developed smart material aeroelastic control concepts for aircraft structures. Dr. Weisshaar is a fellow of the AIAA, a past member of the U.S. Air Force Scientific Advisory Board, and the 2005 recipient of the AIAA Structures, Structural Dynamics, and Materials Award. He received the Air Force Exceptional Civilian Service Decoration in 1998. Dr. Weisshaar has both research and development experience in integrated aircraft structural design coupled to active control devices systematically interfaced toward optimum aircraft performance. His research skills will assist the committee in identifying opportunities in research and development technologies in the systems control of aircraft performance for advanced UAVs.

PANEL D: DYNAMICS, NAVIGATION, AND CONTROL, AND AVIONICS

NANCY G. LEVESON (NAE), *Panel Chair* (see biography above).

RICHARD ABBOTT is a technical fellow emeritus at Lockheed Martin Aeronautics Company in Palmdale, California. He received a Ph.D. in chemical physics from Northern Illinois University, where his research concentrated on cooperative phenomena in molecular systems and the renormalization group. He continued studies as a research associate in statistical mechanics at the University of Chicago s James Franck Institute, where he contributed to theories of energy relaxation in condensed media using Monte Carlo and molecular dynamics techniques. His career includes over 25 years of experience in the areas of guidance, navigation, and control systems design and analysis, sensor data fusion design, and sensor system simulation and modeling for both manned and unmanned aircraft. He has supervised the development and execution of large-scale simulations of complex air vehicles, led the development of the avionics functional architecture for the demonstration/validation phase of the YF-22 program, and developed fault detection and redundancy management algorithms for navigation systems aboard the X-33 single-stage-to-orbit vehicle. He also has served as principal investigator for the DARPA software-enabled control technologies for reliable autonomous control project and has been the co-chair for the Technologies for Autonomous Control session of the IEEE Aerospace Conferences.

CLARK R. BADIE is the business manager for the Displays and Crew Interface Division of Honeywell Aerospace Marketing and Project Management. In addition, he is the U.S. chairperson for the Avionics Harmonization Working Group, which leads the development of new and modified joint federal-European regulations and advisory material for advanced flight-deck displays. Previously, he was the product portfolio manager for strategic marketing and technology, where he aligned avionics product strategies with customer needs and was involved in strategic planning. Other positions he has held at Honeywell include manager of Honeywell Head-Up Displays Development; manager of product marketing and advanced technology for air transport displays; department manager for legacy and head-up displays systems and software engineering; and principal engineer for commercial electronic displays engineering. He has worked extensively with all avionics product disciplines: displays, flight controls, management systems and sensors, as well as certification issues such as software, flight test, safety, and environmental evaluation. Mr. Badie received a B.E. from the Stevens Institute of Technology and an MBA from Arizona State University.

JEFFERY ERICKSON is a senior technical fellow for human factors and crew system design at the Boeing Company, where he is responsible for technical leadership of advanced human–machine interface technology initiatives and their application to aircraft; spacecraft; command, control, communications, and computers; and intelligence, surveillance, and reconnaissance. He is currently assigned to the Boeing Phantom Works, which develops advanced products and provides enabling technologies, prototypes, engineering processes, and advanced methods. Previously he served as the manager of human–system integration for the Boeing Phantom Works and as the manager of crew systems for McDonnell Douglas Aerospace. He is a fellow of the Royal Aeronautical Society and has served on a number of advisory panels, such as the Air Force Scientific Advisory Board, the Naval Research Advisory Committee, and the Department of Defense Technical Advisory Group for Human Factors, among others. Mr. Erickson has received the Exceptional Civilian Service Medal from the Secretary of the Air Force, the Outstanding Achievement Award from McDonnell Aircraft and Missile Systems, and the Engineering Achievement Award from Douglas Aircraft. He received a B.A. in psychology and an M.S. in industrial psychology from California State University, Long Beach.

EPHRAHIM GARCIA is currently associate professor of mechanical and aerospace engineering at Cornell University, where his interests lie in the development of new types of actuation systems utilizing smart material transducers, system-level demonstrations of smart structures applied to defense platforms, and morphing aircraft systems bioinspired intelligent machines. Dr. Garcia served as a program manager in the Defense Sciences Office at DARPA from 1998 to 2002. From 1991 to 1998, he was an assistant and associate professor of mechanical engineering at Vanderbilt University, where he was director of the Center for Intelligent Mechatronics and the Smart Structures Laboratory. In this capacity he directed research in the areas of smart structures, control structure interaction, and bioinspired robotics. From 1991 to 1997, he owned and operated Garman Systems, Inc. (now Dynamic Structures and Materials, LLC), a small engineering corporation that designed and fabricated devices in adaptive structural systems utilizing piezoelectric, electrostrictive, and shape memory alloy materials. Dr. Garcia has been named an ONR Young Investigator, appointed a 1993 Presidential Faculty Fellow by President Clinton, and twice (1990 and 1991) received Summer Faculty Fellowship awards from the Air Force Office of Scientific Research. In 1995, he was named Most Promising Scientist by *Hispanic Engineer* magazine (now *Technica*) and received this award at the Hispanic Engineer National Achievement Awards Conference. Dr. Garcia is author of more than 140 articles, books, chapters, and edited volumes. He serves on the ASME Aerospace Division s Executive Committee and is on the editorial advisory board of *Smart Materials and Structures*. In 2002, Dr. Garcia received ASME s Adaptive Structures Prize for "significant contributions to the sciences and technologies associated with adaptive structures and/or materials systems."

CHARLES L. GUTHRIE is the director of advanced capabilities development for Northrop Grumman s Western Region within the Integrated Systems Sector. He is responsible for programs in space systems, future strike systems, missile defense systems, and naval system integration. Some of his previous positions include director of unmanned systems rapid prototyping and advanced concepts at the Boeing Phantom Works, director of the Joint Strike Fighter air vehicle IPT for Boeing Military Aircraft and Missiles, and director of air vehicle advance design for the Phantom Works. He is a Boeing technical fellow and was named Manager of the Year in 1993 and 1994 by North American Aircraft and the Southern California Area Council, respectively, and Engineer of the Year in 1987 and 1988 by North American Aircraft/Rockwell. Besides earning a B.S. in aerospace engineering from the University of Kansas, Mr. Guthrie has completed a number of technical short courses in topics such as radar, aircraft design, and engine–airframe integration and employee development courses. He works to support the California Polytechnic San Luis Obispo School of Engineering, the University of Kansas Aerospace Department, the Naval Postgraduate School, and Cal State Long Beach by providing industry feedback, serving on advisory boards, and conducting guest lectures. He is a senior member of the AIAA and has served on its Aircraft Design Technical Committee. He is also a senior member of the Association for Unmanned Vehicle Systems International (AUVSI) and a member of the National Management Association (NMA).

ELLIS F. HITT is president of Strategic Systems Solutions. He is responsible for analysis of alternative systems configurations and determining total life cycle cost for the U.S. Coast Guard s HC-130 fleet. He retired in 2005 as a senior manager for Battelle Corporation and was a chairman of the AIAA Digital Avionics Technical Committee. He has a B.S. in electrical engineering from the University of Kansas and an M.S. in electrical engineering from the Air Force Institute of Technology, along with postgraduate studies at OSU and the University of New Mexico. Mr. Hitt is a nationally recognized authority on avionics and flight control systems. He has extensive experience in conceptual, preliminary, and final design of avionics, including navigation, guidance, control, communications, controls and displays, sensors, stores management, weapons delivery, and electrical power subsystems; integration, testing, and analysis of avionics; development of mathematical models and computer programs for performing error analysis, systems simulation and evaluation, and life-cycle cost analyses; and mission software design, development, validation, and verification. Mr. Hitt s responsibilities before retiring from Battelle included senior marketing manager for the Air Force market sector and technical leader on total ownership cost. Prior to promotion to these positions, he was chief engineer, Design Engineering Program, and manager, Avionics Systems Engineering Business Development.

JAMES C. NEIDHOEFER is the CEO of Aerotonomy, Inc., which specializes in the development of advanced UAVs; UAV guidance, navigation, and control systems; and UAV flight-test-related products and services. He is an associate fellow of the AIAA, deputy director of the AIAA Information Systems Group, a past chairman of the AIAA Intelligent Systems Technical Committee, and associate editor for the AIAA *Journal of Aerospace Computing, Information and Communication* and has chaired a number of AIAA conference sessions. He is also a member of Penn State University s Industrial and Professional Advisory Committee. Dr. Neidhoefer was a recipient of the Best Paper Award at the international conference Artificial Neural Networks in Engineering. In addition, he is the author of numerous conference papers, journal articles, and book chapters. He received his B.S., M.S., and Ph.D. from the University of Alabama.

DARRYLL J. PINES is a professor and associate chair in the Department of Aerospace Engineering at UM, College Park, on loan as a program manager in the DARPA Defense Sciences Office. At DARPA, he is the program manager of the sensor dart, long gun, XNAV, and NAV programs. As a former DOE technical staff member working at the LLNL, Dr. Pines developed advanced guidance algorithms for interceptors and the final approach algorithm for the 1994 Clementine flyby mission, which was the first probe to discover water near the south pole of the Moon. His research interests include smart materials/structures technology, structural health monitoring, structural dynamics, micro and nano air vehicle systems, and vehicle guidance, control, and navigation. He has published over five book chapters and 200 journal/conference articles on topics in structural dynamics, damage detection, and vehicle flight dynamics, control, and navigation. He is an associate fellow of the AIAA, a fellow of the Institute of Physics, and chairs the Adaptive Structures Technical Committee of the AIAA. Dr. Pines graduated from MIT with Ph.D. and M.S. degrees in mechanical engineering and earned his B.S. degree from UC Berkeley in the same discipline.

JAMES RANKIN is the director of the Avionics Engineering Center at Ohio University. He holds a Ph.D. in electrical engineering from Iowa State University. His M.S.E.E. is also from Iowa State University and his B.S.E.E. from the South Dakota School of Mines and Technology. He has more than 25 years of experience in avionics research and design from both academic and industrial perspectives. Dr. Rankin has been involved with the NASA small aircraft transportation system. Previously, he was the PI on terminal area controller-pilot data link communications research, which was integral to NASA s low-visibility landing and surface operations flight test at Atlanta Hartsfield airport (1997) and the NASA runway incursion prevention system test at Dallas-Fort Worth airport (2000). Dr. Rankin was with Rockwell Collins, where his projects included airborne collision avoidance systems, four-dimensional flight management systems, and air transport display systems. As a senior member (2003) of the IEEE, he was twice elected (1999, 2002) to 3-year terms on the IEEE Aerospace and Electronic Systems board of governors. He is a senior member (2003) of the AIAA and was elected chair of the AIAA Digital Avionics Technical Committee in 2003. Dr. Rankin also has memberships in the Institute of Navigation (ION), Air Traffic Control Association, International Loran Association, and the Aircraft Owners and Pilots Association. He is an active member of the aviation community as a certified flight instructor with single-engine, multiengine, and instrument ratings.

JASON L. SPEYER (NAE) is currently a professor and past chairman in the Mechanical, Aerospace and Nuclear Engineering Department (now the Mechanical and Aerospace Engineering Department) at UCLA. He spent a research leave as Lady Davis Visiting Professor at the Technion (Israel Institute of Technology) in 1983 and was the 1990 Jerome C. Hunsaker Visiting Professor of Aeronautics and Astronautics at MIT. His industrial experience includes research at Boeing, Raytheon, Analytical Mechanics Associated, and the Charles Stark Draper Laboratory. He was the Harry H. Power Professor in Engineering Mechanics, University of Texas, Austin. Dr. Speyer was twice elected member of the board of governors of the IEEE Control Systems Society and chairman of the Technical Committee on Aerospace Controls. He served as an associate editor for *Technical Notes and Correspondence* (1975-1976) and *Stochastic Control* (1978-1979), *IEEE Transactions on Automatic Control*, the *AIAA Journal of Spacecraft and Rockets* (1976-1977), the *AIAA Journal of Guidance and Control* (1977-1978), and the *Journal of Optimization Theory and Applications* (1981-present). From October 1987 to October 1991 and from October 1997 to October 2001, he served as a member of the Air Force Scientific Advisory Board. He is a fellow of both the AIAA and the IEEE (life fellow). He was the recipient of the AIAA Mechanics and Control of Flight Award (1985), the AIAA Dryden Lectureship in Research (1995), the IEEE Third Millennium Medal (2000), and the Air Force Exceptional Civilian Decoration (1991 and 2001). Dr. Speyer received his B.S. in aeronautics and astronautics from MIT in 1960 and his Ph.D. in applied mathematics from Harvard University in 1968.

JOHN VALASEK (see biography above).

PANEL E: INTELLIGENT AND AUTONOMOUS SYSTEMS, OPERATIONS AND DECISION MAKING, HUMAN INTEGRATED SYSTEMS, AND NETWORKING AND COMMUNICATIONS

EDMOND L. SOLIDAY, *Panel Chair* (see biography above).

ELLA ATKINS is an assistant professor in the Department of Aerospace Engineering at UM, where she cofounded the Autonomous Vehicles Laboratory and is an active researcher in the Space Systems Laboratory and Alfred Gessow Rotorcraft Center. She holds B.S. and M.S. degrees in aeronautics and astronautics from MIT and M.S. and Ph.D. degrees in computer science and engineering from the University of Michigan. Her research integrates task-level planning and scheduling with trajectory optimization algorithms for safety-critical robotic systems and flight vehicles. Dr. Atkins is an active member of the AIAA Intelligent Systems technical committee, associate editor of the *AIAA Journal of Aerospace Computing, Information, and Communication*, and is a private pilot. She has written more than 50 papers that develop and apply real-time, artificial intelligence and optimization strategies to aerospace applications.

TAMER BASAR (NAE) is the Fredric G. and Elizabeth H. Nearing Professor of Electrical and Computer Engineering at the University of Illinois at Urbana-Champaign (UIUC). He is also a professor in the Center for Advanced Study of UIUC. His research interests include robust nonlinear and adaptive control; routing, pricing, and congestion control in communication networks; control over wired and wireless networks; mobile computing; and risk-sensitive estimation and control. He is a fellow of the IEEE as well as of the International Federation of Automatic Control and a past president of the Control Systems Society and the International Society of Dynamic Games. He has edited a number of books, book series, and journals, including *Automatica* and *IEEE Transactions on Automatic Control*. He has authored or coauthored over 150 journal articles and book chapters, over 200 conference publications and several books. He has received the Giorgio Quazza Medal of the International Federation of Automatic Control, the Hendrik W. Bode Lecture Prize of the IEEE Control Systems Society, the IEEE Millennium Medal, and the Medal of Science of Turkey, among many other awards. Dr. Basar received his B.S.E.E. from Robert College, Istanbul, and M.S., M.Phil., and Ph.D. degrees in engineering and applied science at Yale University.

THOMAS Q. CARNEY is professor of aviation technology and head of the Department of Aviation Technology at Purdue University, where he has taught since 1972. Dr. Carney has over 37 years of experience as a pilot, with more than 10,130 flight hours, and holds the ATP certificate with multiengine, Beechjet, and Mitsubishi Diamond type ratings in addition to the Certified Flight Instructor certificate with airplane single-engine, multiengine, and instrument ratings. Dr. Carney s primary teaching areas in aviation include advanced aviation meteorology, high-performance turbine operations, high-altitude flight, and corporate flight department management. Dr. Carney holds an M.S. and a Ph.D. in atmospheric science; his primary areas of interest in atmospheric science include aviation meteorology and the impact of weather on aviation operations, synoptic-scale dynamics and energetics, and the interactions between synoptic- and mesoscale motion fields. Dr. Carney is the senior editor of the *Collegiate Aviation Review* and a member of the editorial boards of the *Journal of Aviation/Aerospace Education and Research* and the *Journal of Air Transportation*. He serves on the board of directors of the Council on Aviation Accreditation (CAA), the Certified Aviation Manager governing board (and is currently serving as that board s first chairperson), and is chairperson of the CAA Standards Committee. Dr. Carney is an active consultant in corporate flight operations and an expert witness in litigation involving flight operations and aviation meteorology. In 2002, he was awarded the William A. Wheatley award by the University Aviation Association, given annually to a professional educator of more than 10 years experience, who has made outstanding contributions to aerospace education. In 2004, he was designated a Certified Aviation Manager by the Certified Aviation Manager governing board.

JOHN-PAUL CLARKE is an associate professor in the School of Aerospace Engineering and director of the Air Transportation Laboratory at the Georgia Institute of Technology (Georgia Tech). His research and teaching address issues of optimization and robustness in aircraft and airline operations, air traffic management, and the environmental impact of aviation. He received his S.B. (1991), S.M. (1992), and Sc.D. (1997) from MIT and was a faculty member at MIT prior to moving to Georgia Tech. He has also been a researcher at the NASA Jet Propulsion Laboratory and a visiting scholar at the Boeing Company. Dr. Clarke is a member of the Airline Group of the International Federation of Operations Research Societies, AIAA, the Institute for Operations Research and the Management Sciences (INFORMS), ION, and Sigma Xi, The Scientific Research Society. He serves on several national and international committees, including the FAA Research Engineering and Development Committee (REDAC), the AIAA Air Transportation Systems Technical Committee, and the SAE Aircraft Noise Committee. Dr. Clarke was the first director of the Partnership for AiR Transportation Noise and Emissions Research (PARTNER) at the Center of Excellence for Aviation Noise and Aircraft Emissions Mitigation and is an active researcher in both PARTNER and the National Center of Excellence for Aviation Operations Research (NEXTOR). In 1999, he was awarded the AIAA/AAAE/ACC Jay Hollingsworth Speas Airport Award, and in 2003, he was awarded the FAA Excellence in Aviation Award. Dr. Clarke is currently a member of ASEB.

MICHAEL DeWALT is a former national resource specialist for software for the FAA. Currently, he is the chief scientist of aviation systems for Certification Services, Inc., a consulting firm for electronic equipment in aviation. In the FAA, Mr. DeWalt was responsible for providing technical guidance on policy, training, research, and development in airborne software and its associated ground-based systems; he was the technical focal point for industry and the FAA for evaluation of new technology and interpretation of existing policy as applied to aircraft systems. Prior to becoming the FAA s national resource specialist, Mr. DeWalt worked as a software life-cycle consultant for Telos Consulting Services, as a software control system engineer for Pacific Technologies, Inc., as an avionics certification engineer for the FAA, as software focus for the Boeing 757/767 autopilot, and as a digital and analog avionics engineer for Honeywell Flight Systems. He has given many presentations at national and international conferences on design assurance of safety-critical, software-based systems. He is a member of IEEE and has participated as a member of working groups drafting new standards for safety-critical software and revising IEEE document 1012, "Standards for Verification and Validation," and is a member of the Association of Computing Machinery. He received a B.S. in electrical engineering from the University of Washington and an M.S. in software engineering from Seattle University. Mr. DeWalt previously served on two NRC study groups.

FRANK L. FRISBIE is vice president for strategic planning in the transportation sector of Apptis, Inc. He was a longtime senior executive with the FAA and DoD and was vice president and senior client executive for civil aviation with Northrop Grumman Information Technology before joining Apptis in January 2005. He joined the FAA in 1958, where he held a variety of positions. In his last two posts, he was directly responsible for research, development, system engineering, acquisition, deployment, and maintenance of all 20,000 air traffic control facilities in the United States. Mr. Frisbie was awarded the Glen A. Gilbert Memorial Award in 2002 by the Air Traffic Control Association (ATCA) for his long-standing contributions to the air traffic control and civil aviation communities. He has been involved with the development, deployment, maintenance, and operation of virtually every system employed in the U.S. civil aviation infrastructure. He earned his B.E.E. degree from Manhattan College and his M.B.A. degree from American University. He is a member of the NASA Aeronautics Research Advisory Board, a member of the Russian Academy of Navigation and Motion Control, and he holds a professional engineer s license.

ANDREW LACHER is a research strategist working on system transformation and security for MITRE Corporation s Center for Advanced Aviation Systems Development (CAASD), where he helps coordinate internally directed R&D efforts as well as cross-corporate research issues associated with unmanned aircraft systems. He also manages CAASD s collaboration and interaction with NASA and works closely with the FAA Joint Planning and Development Office (JPDO) on the definition of NGATS. Mr. Lacher is a member of the JPDO s Agile Air Traffic Services integrated product team and its executive committee. He serves on the FAA s RE&D Advisory Committee s Air Traffic Services subcommittee and on the NEXTOR steering committee. He was a leader in formulation and eventual implementation of the collaborative decision-making (CDM) approach for air traffic management and led a number of studies that helped illustrate the benefit and feasibility of CDM and helped define many of the early concepts. Previously, he was a product manager for Orbcomm and a strategic information technology consultant working with small airlines. He is an associate fellow of the American Institute of Aeronautics and Astronautics and a member of the Airline Dispatcher Foundation, INFORMS, and the Airline Group of the International Federation of Operational Research Societies (AGIFORS). Mr. Lacher received both an M.S. in operations research and a B.S. in electrical engineering from the George Washington University.

RAYMOND R. LaFREY retired as manager of the air traffic control mission area at MIT s Lincoln Laboratory in 2003. His responsibilities encompassed surveillance, navigation, communications, and weather sensing and involved 150 staff and support personnel. Key elements include the development of airport surface technology, modern open architecture surveillance systems, and integrated airport and regional weather systems that provide time-critical weather knowledge directly to operational staff at FAA and airline facilities. After receiving a B.S.E.E. and an M.S.E.E. at Michigan State University, Mr. LaFrey served 6 years in the U.S. Army as a Signal Corps officer, installing satellite communications ground stations in Europe, Africa, and Vietnam. He joined MIT Lincoln Laboratory in 1969 and began developing air traffic control technology in 1974. From 1977 to 1982, he led the team that developed the first TCAS II flight hardware and conducted surveillance flight-test activities. During the 1980s he led the development and flight-testing of a GPS navigation set for small aircraft. He also led the Precision Runway Monitor Program, which enabled simultaneous instrument approaches to parallel runways spaced as close as 3,000 feet. He has served on a variety of advisory boards, including the American Astronautical Society s (AAS s) Recovery Team and a Defense Science Board task force on aviation safety. Mr. LaFrey is currently a member of the FAA s REDAC and the REDAC Air Traffic Services Subcommittee, and he chaired a REDAC study on transitioning research to operational capabilities. Mr. LaFrey has received FAA awards for his work on the traffic collision avoidance system, the precision runway monitor, and the ASR-9. He is also an inactive instrument-rated pilot.

CARL McCULLOUGH retired from the federal service in November 2005. His last position, as a member of the Senior Executive Service, was associate director for airspace, ranges, and airfield operations, Office of the Deputy Chief of Staff for Air and Space Operations, Headquarters of the U.S. Air Force, Washington, D.C. In addition, he is the executive director for the DoD Policy Board on Federal Aviation. Mr. McCullough is responsible for providing worldwide access to airspace and ranges, as well as deployable combat-capable air traffic control, airfield management, and base operations personnel and equipment. He also represents DoD positions in support of the U.S. National Airspace System as a seamless partner with the FAA. In addition, he provides strategic vision for Air Force and DoD participation and partnering in modernization of U.S. and global air transportation systems, as well as civil aviation policy formulation, airspace and aircraft access, air traffic control infrastructure, and international cooperation, to include all regional airspace initiatives. Mr. McCullough is the primary point of contact between the DoD and the Department of Transportation on domestic and international civil aviation issues with potential impact on military flying operations and air defense. Previously, Mr. McCullough served 24 years as a naval aviator. In his final tour he commanded the Naval Plant Representative Office at McDonnell Douglas Corporation in St. Louis. Following his retirement from the Navy in 1990, Mr. McCullough served with McDonnell Douglas Helicopter Company as general manager of its MD-500 program and then as vice president of the RAIL Company s Eastern Region. From 1993 to 2002, Mr. McCullough held numerous managerial and executive assignments with the FAA, including program manager for the wind shear and weather radar programs, program manager for satellite navigation systems, and director of the Office of Communication, Navigation, and Surveillance Systems. In May 2002, he was assigned to the White House Office of Science and Technology Policy as a Department of Transportation representative to the National Science and Technology Council. He is a graduate of the U.S. Naval Academy and the Naval Postgraduate School.

AMY PRITCHETT (see biography above).

DONALD W. RICHARDSON is a fellow of the AIAA and has been a member of AIAA continuously for 57 years. He is currently the immediate past president of the AIAA and served as the president of AIAA in 2004 and 2005. He has been named as a fellow of the Royal Aeronautical Society and was recently co-opted by the Royal Aeronautical Society to serve on its Engineering Council for 2003-2004. He was awarded the NASA Public Service Medal in 2002 for his work in reinvigorating U.S. federal funding for R&D in aeronautics. He holds bachelor s, master s, and Ph.D. degrees in aeronautical and mechanical engineering. A commercial instrument pilot with multiengine land and seaplane ratings, he has been an active pilot for 58 years. His engineering career included assignments as an aerodynamics and flight test engineer, research pilot, and engineering manager. He is presently employed as a vice president of SAIC, where he is responsible for all FAA and civil aviation corporate activities.

NADINE SARTER is currently an associate professor in the Department of Industrial and Operations Engineering and the Center for Ergonomics at the University of Michigan. She received her M.S. degree in experimental/applied psychology from the University of Hamburg (Germany) in 1983 and her Ph.D. in industrial and systems engineering from OSU in 1994. Dr. Sarter s primary research interests include (1) the design of multimodal interfaces in support of effective human–machine communication and coordination and computer-supported collaborative work, (2) the development of robust and transparent decision support systems, and (3) the use of design and training to support error management in a variety of complex event-driven domains, such as aviation and military operations. From 1994 to 1996, she served as technical advisor to the FAA Human Factors Team to provide recommendations for the design and operation of and training for advanced glass cockpit aircraft. For her research in the aviation domain, she received *Aviation Week and Space Technology* s Aerospace Laurels Award for Outstanding Achievement in the Field of Commercial Air Transport in 1996 and the TGIR (Turning Goals Into Reality) Award as member of the UIUC Aircraft Icing Project Team from NASA Glenn Research Center in 2001. Her aviation-related research was supported by NASA, the FAA, and an NSF CAREER award.

I

Speakers

The National Research Council appreciates the efforts of and the information provided by the individuals who volunteered their time to speak at the meetings of the steering committee and panels:

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Aaron Auslender, NASA Langley Research Center
Milind Bakhle, NASA Glenn Research Center
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Joan Bauerlein, Federal Aviation Administration
Chris Benich, Honeywell Aerospace
Isaiah Blankson, NASA Glenn Research Center
Iain Boyd, University of Michigan
Jack Boyd, Cytec Engineered Materials
Irene Brahmakulam, Office of Management and Budget
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Wayne Bryant, NASA Langley Research Center
Robert Bucci, Alcoa Technical Center
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Scott Cruzen, Williams International
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Gregg Dvorak, Office of Science and Technology Policy
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Dick Johnson, Gulfstream Aerospace Corporation
Sylvia Johnson, NASA Ames Research Center
Walter Jones, Air Force Research Laboratory
Suresh Joshi, NASA Langley Research Center
Joel Kaplan, U.S. Congress, House Appropriations Committee, Subcommittee on Science, State, Justice, and Commerce
Fred Krause, GE Aircraft Engines
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Erik Zahn, The Boeing Company
John Zuk, NASA Ames Research Center

J

Acronyms and Abbreviations

3-D	three-dimensional
ACARE	Advisory Council for Aeronautics Research in Europe
ADS-B	automatic dependent surveillance broadcast
AFRL	Air Force Research Laboratory
Al-Li	aluminum-lithium alloys
ATM	air traffic management
CBM	condition-based maintenance
CFD	computational fluid dynamics
CMC	ceramic matrix composite
CNS	communications, navigation, and surveillance
CO	carbon monoxide
CO_2	carbon dioxide
COTS	commercial off the shelf
DARPA	Defense Advanced Research Projects Agency
DoD	Department of Defense
DOE	Department of Energy
DHS	Department of Homeland Security
DNL	day-night average sound level
ESTOL	extremely short takeoff and landing
FAA	Federal Aviation Administration
FFRDC	federally funded research and development center
FOD	foreign object damage
GLONASS	Global Navigation Satellite System
GNC	guidance, navigation, and control
GOES	Geostationary Operational Environmental Satellites
GPS	Global Positioning System
H_2O	water

ICAO	International Civil Aviation Organization
ILS	instrument landing system
ITAR	International Traffic in Arms Regulations
IVHM	integrated vehicle health management
JPDO	Joint Planning and Development Office
JPL	Jet Propulsion Laboratory
JSF	Joint Strike Fighter
L/D	lift:drag ratio
LDI	lean direct injection
LES	large eddy simulation
LPP	lean, premixed, prevaporized
MDO	multidisciplinary design optimization
MEA	more-electric aircraft
MEANS	Materials Engineering for Affordable New Systems (Program)
METAR	meteorological aviation report
MURI	Multidisciplinary University Research Initiative
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NDE	nondestructive evaluation
NGATS	Next Generation Air Transportation System
NOAA	National Oceanic and Atmospheric Agency
NO_x	oxides of nitrogen
NRC	National Research Council
PIREP	pilot report
PM	particulate matter
PMAD	power management and distribution
QFD	quality function deployment
R&D	research and development
R&T	research and technology
RANS	Reynolds-averaged Navier-Stokes
RNP	required navigational performance
RVSM	Reduced Vertical Separation Minima
SIGMET	significant meteorological information
SMA	shape memory alloys
SO_x	oxides of sulfur
SSTO	single stage to orbit
STOL	short takeoff and landing
TAF	terminal area forecast
TBCC	turbine-based combined cycle
TCP	Transmission Control Protocol
TPS	thermal protection system
TRL	technology readiness level
TSTO	two stage to orbit
T/W	thrust to weight ratio

UAV	unmanned air vehicle
UHC	unburned hydrocarbons
USAF	United States Air Force
VGC	variable geometry chevron
VLJ	very light jet
VMS	vehicle management systems
VOR	very high frequency (VHF) omnidirectional range
V/STOL	vertical and short takeoff and landing
VTOL	vertical takeoff and landing

THE NATIONAL ACADEMY OF SCIENCES' DECADAL PLAN FOR AERONAUTICS: NASA'S RESPONSE

TUESDAY, SEPTEMBER 26, 2006

HOUSE OF REPRESENTATIVES,
SUBCOMMITTEE ON SPACE AND AERONAUTICS,
COMMITTEE ON SCIENCE,
Washington, DC.

The Subcommittee met, pursuant to call, at 10:05 a.m., in Room 2318 of the Rayburn House Office Building, Hon. Ken Calvert [Chairman of the Subcommittee] presiding.

SUBCOMMITTEE ON SPACE AND AERONAUTICS
COMMITTEE ON SCIENCE
U.S. HOUSE OF REPRESENTATIVES
WASHINGTON, DC 20515

Hearing on

The National Academy of Sciences' Decadal Plan for Aeronautics: NASA's Response

Tuesday, September 26, 2006
10:00 a.m. – 12:00 noon
2318 Rayburn House Office Building

WITNESS LIST

Dr. Lisa Porter
Associate Administrator for Aeronautics
National Aeronautics and Space Administration

Maj. Gen. William Hoover (Ret.)
Co-Chair
National Academy of Sciences' Steering Committee

HEARING CHARTER

SUBCOMMITTEE ON SPACE AND AERONAUTICS
COMMITTEE ON SCIENCE
U.S. HOUSE OF REPRESENTATIVES

The National Academy of Sciences' Decadal Plan for Aeronautics: NASA's Response

TUESDAY, SEPTEMBER 26, 2006
10:00 A.M.–12:00 P.M.
2318 RAYBURN HOUSE OFFICE BUILDING

Purpose

On Tuesday, September 26, 2006, at 10:00 a.m., the Space and Aeronautics Subcommittee will hold a hearing on the reaction of the National Aeronautics and Space Administration (NASA) to recommendations from the National Academy of Sciences on how NASA should run its civil aeronautics research and development (R&D) program. The hearing is a follow-up to a Subcommittee hearing on July 18, 2006, which took testimony from four witnesses representing industry, academia, and the National Academy of Sciences on two reports recently published by the Academy—*Aeronautics Innovation: NASA's Challenges and Opportunities,* published in early May; and the first ever *Decadal Survey of Civil Aeronautics: Foundation for the Future,* published in early June.

A full copy of the July 18 hearing charter can be found here: *http://www.house.gov/science/hearings/space06/July%2018/Charter.pdf*

Witnesses

Dr. Lisa Porter has been serving as NASA Associate Administrator for Aeronautics Research Mission Directorate since October 2005. She previously worked at the Defense Advanced Research Projects Agency. Dr. Porter received her doctorate in applied physics from Stanford University.

Gen. William Hoover (Air Force, retired) was Co-Chair of the National Academy of Sciences' Steering Committee that produced the report: *Decadal Survey of Civil Aeronautics: Foundation for the Future.*

Overarching Questions

1. What should the goals, strategies and activities be for NASA's aeronautics research and development program?
2. What should NASA be doing to ensure that its research is relevant to the long-term needs of industry and is used by industry? What should NASA be doing to help keep the academic research enterprise healthy and to ensure an adequate supply of aeronautics engineers and researchers?

Highlights of the July 18 Hearing

Opening Statements—

Dr. Paul Kaminski, Chair, Committee on Decadal Survey of Aeronautics. His opening statement described the committee's methods used to develop its 51 priority challenges and eight recommendations. Additionally, he noted that the committee, in its report, urged NASA to:

- Create a more balanced split in the allocation of aeronautics R&D funding between in-house research and external research. (The committee estimated that NASA was spending 93 percent of its aeronautics research budget on NASA engineers and technical specialists, with the remainder—$50 million—being spent on external research.)

- Closely coordinate and cooperate with other public and private organizations to take advantage of advances in cross-cutting technology funded by federal agencies and private industry.
- Develop each new technology to a level of readiness appropriate for that technology, given that industry's interest in continuing the development of new technologies varies depending on urgency and expected payoff.
- Invest in research associated with improved ground and flight test facilities and diagnostics, in coordination with the Department of Defense and industry.

Dr. Steve Merrill, Executive Director of the Academy's Board on Science, Technology and Economic Policy, and manager of the committee that produced Aeronautics Innovation. His opening statement emphasized the growing "discrepancy between the needs said to be served by NASA's program and the resources available to it." He also repeated general guidance offered in the report, including:

- A strategic focus for NASA that is in line with its budget, personnel, and technical capabilities is likely to result in a reduced mission scope and portfolio, but one with greater potential to achieve innovation in air transportation.
- The portfolio should reflect stakeholder needs. There should be open consultation with customers and users.
- There is a strong case for NASA to continue to pursue "public good" areas of R&D work—those closely related to safe and efficient air traffic management, environmentally more benign aviation operations (i.e., pollution and noise reduction), and the certification of equipment and standards.
- NASA should continue to have a diversified portfolio in terms of the stage of technology being developed, even if that means significantly fewer projects.
- Refocusing NASA aeronautics program exclusively on fundamental research may appear to be a reasonable strategy given the current outlook for funding, but it risks losing the support of industry.

Dr. Mike Romanowski, Vice President of Civil Aviation, Aerospace Industries Association. His opening statement described the decline in federal aeronautics R&D investment and the threats this trend posed to the future of the U.S. aviation industry, and to our national security and prosperity. Dr. Romanowski also stressed the importance of NASA and industry working closely together to plan and execute R&D programs.

Dr. Parviz Moin, Professor of Mechanical Engineering and Director of the Institute for Computational and Mathematical Engineering, Stanford University. In his opening statement, Dr. Moin agreed with the current direction of NASA's aeronautics R&D program in light of the limited budget with which it has to operate. He argued that:

- NASA's emphasis on foundational research is appropriate;
- The biggest challenges facing the U.S. civil aviation system are related to air traffic management systems, and environmental issues (noise and pollution); and
- Computational modeling will become much more integral to the design of next-generation aircraft, but at the same time, he emphasized that much research in computer-aided modeling needs to be pursued.

Summary of Issues Discussed During Q&A—

- *Decadal Survey.* All witnesses agreed with the Decadal Survey's recommendations, although Dr. Romanowksi suggested that the survey should have given air traffic management technology R&D greater emphasis.
- *NASA's aeronautics R&D budget.* Dr. Kaminski, offering a personal view, suggested the budget ought to be doubled. Drs. Romanowski and Merrill expressed strong concerns about the declining trend in aeronautics funding but did not suggest a preferred funding level.
- *NASA funding for external research.* Dr. Kaminski noted that the survey suggested the current balance between NASA in-house and external needed rebalancing, but the report did not specify what the balance ought to be.
- *Basic research vs. technology demonstrations.* Drs. Kaminski, Merrill and Romanowski stated that NASA must undertake demonstration projects on a selective basis.

Full Cost Simplification

Recently NASA implemented an accounting change that should benefit its aeronautics research program. In mid-August NASA notified Congress that it was simplifying the method used to calculate "overhead" rates charged by NASA Centers against agency-funded projects and to external customers. Under the new system, a single uniform rate for Center Management and Overhead (CMO) will be applied to all Centers. Previously each Center's overhead rate was unique (based—in part—on size, personnel, and infrastructure) and the aeronautics research centers, housing many of the oldest and largest test facilities within NASA, had relatively high rates. The new, simplified formula will allow aeronautics centers to charge lower rates, thus allowing them to be more competitive, especially with external customers.

The formula change, though, could give the unintentional and false appearance that NASA is spending less on aeronautics research. For example, the FY07 budget request for the Aeronautics Research Mission Directorate is $724 million; substituting the new overhead calculation, it would appear aeronautics R&D is being reduced by almost $200 million. In a letter to the Committee, Administrator Griffin stated that "the amount of funding going to each research Center is unchanged, the amount of funding for direct program and project activity is unchanged, the total amount of funding for overhead is unchanged, and the total NASA budget is unchanged.. . .Let me assure you that there is zero change in Aeronautics Research content as a result of this change in accounting."

DOD Memorandums of Understanding

In early August, NASA and the Department of the Air Force signed a Memorandum of Understanding (MOU) creating a partnership to coordinate aeronautics research efforts. NASA and the Air Force agreed to: (1) include each other in their major program reviews related to aeronautics research; (2) avoid duplication of aeronautics research; (3) share research data when security guidelines permit; and (4) assist each other, as needed, in program peer reviews and proposal evaluations. The MOU creates an Air Force/NASA Executive Research Committee to oversee these efforts. The MOU also states that each agency shall fund its own participation in the endeavor, and that nothing in the MOU alters the statutory authorities of NASA or the Air Force. NASA is now seeking to update an existing MOU with the Department of the Army, as well as enter a separate MOU with the Department of Defense.

Chairman CALVERT. If everybody would like to take their seat, we will call the hearing to order. Without objection, the Chair will be granted the authority to recess the Committee at any time. Hearing no objection, so ordered.

I will begin my opening statement.

Yesterday afternoon, we returned from NASA'S Glenn Research Center. It was the ninth Center that I have visited since becoming Chairman last year. I certainly received a warm welcome from the Center as well as the constituent Members of Congress. Each of these visits have been a remarkable learning experience, and I would encourage some of the other Members to join me next time we schedule our next Center, which is the last Center I am going to be visiting. This is going to be the 10th, which will be the Langley Research Center in Virginia, some place pretty close to my colleague to my left. Maybe we can get over there and visit some of the other beautiful attractions in that beautiful part of the State. We will probably fly down Sunday, November 12, and spend Monday, November 13 at the Center. I invite others to join us in what has been an enlightening experience for us all.

Today we are holding the second of two hearings on NASA's efforts to refocus and reshape the nation's civil and aeronautics research program. The first hearing was held earlier this year on July 18. At that time, we heard from our four witnesses representing industry, academia, the National Academy of Science. The hearing focused on two recently published reports by the National Research Council. We asked our panel at the earlier hearing to contrast and compare the recommendations of the report for what they understand NASA is actually doing in its efforts to reshape and to strengthen its aeronautics research and development program.

Today, the Subcommittee is honored to have Dr. Lisa Porter, who also traveled with us yesterday to the Glenn Research Center with our Co-Del, NASA Associate Administrator for the Aeronautics Research Mission Directorate; and General Hoover, the Co-Chair of the National Academy's Steering Committee, which produced the first ever decadal survey of civil aeronautics. I want to welcome them and thank them for appearing before our subcommittee on this subject so important to our nation.

Federally-sponsored aeronautics research began in earnest in 1915 with the establishment of the National Advisory Committee for Aeronautics, NACA, and the Langley Memorial Aeronautical Laboratory. In the years since, Langley and its sister aeronautics research Centers at Glenn, Ames, and Dryden have produced enormous technical and intellectual advances to our understanding of manned flight.

The work is far from over. I visited each of these NASA Centers, except for Langley, which I mentioned. It is on my schedule in November. Each Center is impressive with its intellectual capital and the great projects that are being undertaken by each. The research at these Centers has enabled the country to achieve supremacy in military and civil aeronautics and related technology that continues to this day.

Having said that, during the past decade the level of federal investment in civil aeronautics research and development has significantly declined. In fiscal year 2007, aeronautics R&D at NASA will account for less than five percent of the Agency's budget. While it may not be entirely fair to portray this level of funding as an indication of NASA's commitment to aeronautics research, there is no doubt that aeronautics is working in a very constrained budget atmosphere.

Given these trends, the questions we need to ask ourselves is whether we as a country are jeopardizing our nation's future capability to continue to develop and produce state-of-the-art aircraft that are safe, efficient, and environmentally benign. Equally important, are we competitive with foreign manufactured aircraft? Will our air traffic management system be able to accommodate in a timely way the projected growth in air traffic? The answers hinge on NASA's ability to devote the necessary resources and put in place the best strategies and programs.

The Decadal Survey of Civil Aeronautics is intended to offer NASA strategic guidance for its aeronautics R&D program. It identifies four priority strategic objectives, an excellent report and one that should be very useful to NASA. At our July hearing, witnesses agreed with the Decadal Survey's recommendations. They also suggested that NASA needs to increase its aeronautics budget, and they stressed the importance of maturing promising technologies to a level that would enable adoption by other governmental agencies or industry. They urged NASA to consult and work with industry on a routine basis and to increase the amount of funding for external research.

I look forward to hearing the testimony of our witnesses on the subject.

[The prepared statement of Chairman Calvert follows:]

PREPARED STATEMENT OF CHAIRMAN KEN CALVERT

Today we are holding the second of two hearings on NASA's efforts to refocus and to reshape the Nation's civil aeronautics research program. The first hearing was held earlier this year on July 18. At that time we heard from four witnesses representing industry, academia, and the National Academy of Sciences. The hearing focused on two recently published reports by the National Research Council. We asked our panel at the earlier hearing to contrast and compare the recommendations of the reports with what they understand NASA is actually doing in its efforts to reshape and to strengthen its aeronautics research and development program.

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I look forward to hearing the testimony of our witnesses on these subjects and I turn now to our Subcommittee Ranking Member, Rep. Udall, for his opening statement.

Chairman CALVERT. I turn now to our Subcommittee Ranking Member, my friend from the beautiful State of Colorado, where all that water comes—thank God for gravity—downhill, for his opening statement. Mr. Udall.

Mr. UDALL. Thank you, Mr. Chairman. Good morning. I would also like to join Chairman Calvert in welcoming our two witnesses, Dr. Porter, General. It is great to have you here.

As Chairman Calvert did, I would like to use my opening remarks to also provide some context for today's hearing and explain why I think it is important to undertake some serious oversight in this area.

In short, I believe that the ill-advised budget cuts and changes in NASA's priorities are putting the Nation at risk of losing critical aeronautics research and developmental capabilities. These are capabilities that we need now more than ever if we are to improve the safety and reliability of our air transportation system, while at the same time increasing its capacity to meet projected demand, increasing its efficiency and performance and reducing its environmental and energy impacts. Moreover, these same aeronautics R&D capabilities have the ability to contribute to our national defense and the security of our home land, as has been amply demonstrated in the past.

Yet, instead of investing more in the highly productive aeronautics enterprise that has been built up within NASA and its predecessor organization over the last nine decades, NASA is in the process of dismantling those capabilities as it turns its attention elsewhere and reallocates resources to new ventures. Because the budgetary erosion has been incremental, it is easy to underestimate the magnitude of the damage that is being done. Perhaps the following statistics will help clarify the problem.

In 1994, NASA spent more than $1.8 billion—now, that is in 2006 dollars—on aeronautics R&D. For fiscal year 2007, on the other hand, NASA has requested just $724 million, or two and a half times less than the 1994 investment level. Another statistic: the Administration's budget plan for NASA's aeronautics program would have aeronautics funding decline by 32 percent between fiscal year 2004 and fiscal year 2007, with a continuing decline in purchasing power envisioned for at least the rest of the decade.

As Dr. Paul Kaminski, the Chair of the National Academy's Decadal Survey of Civil Aeronautics has warned, "This budgetary trend will make it increasingly difficult for NASA to build a solid foundation for the future." Unfortunately, those budget cuts have been coupled to a restructuring of its aeronautics program that appears to be backing away from the highly productive partnership between government, industry, and academia, which has long been the hallmark of NASA and its predecessor organizations' aeronautics research programs.

Instead, NASA has turned to a program more narrowly focused on fundamental research, the vast majority of which is to be carried out in-house by NASA. While I applaud the strengthening of NASA's fundamental aeronautics research program, which has suffered in recent years due to the overall squeeze on NASA's aeronautics budget, that move unfortunately is coming at the expense of a broader vision of what NASA's aeronautics R&D should be about.

Again, let me quote the words of several witnesses who testified at our hearing on July 18. For example, Dr. Merrill of the National Academy stated "The Committee concluded that support of fundamental research is important but not sufficient to accomplish the Federal Government's legitimate role in advancing the air transportation system. There will remain a "Valley of Death" between fundamental research results and systems innovation. Moreover, the support of technology users needed to sustain NASA's role in aeronautics will very likely continue to wane, undermining even its contributions to research."

Dr. Michael Romanowski of the Aerospace Industries Associated noted that "Both government and the general public depend on industry to incorporate the results of NASA's research into new systems and products that improve our nation's infrastructure and quality of life. Therefore, it is imperative that NASA's aeronautics research program includes a robust transitional research component that lays a solid foundation for industry to explore inventive ways to apply that research and perform a follow-up on applied R&D necessary for market and public applications." He added that "Under the restructuring of NASA's aeronautics program, industry's role has been very limited. The new NASA aeronautics R&D program allowed only seven percent of the aeronautics R&D budget to be expended on external research contracts."

Dr. Kaminski of the National Academies echoed those concerns in reporting on his committee's findings, mainly that such a limited fraction devoted to external research "would not adequately involve industry or academia, or serve the best interests of NASA or the Nation."

My concerns, however, extend beyond the lack of adequate participation by industry and academia and NASA's restructured aeronautics research program. They also go to my concerns that NASA's budgetary situation and its changed priorities are causing it to reduce its commitment to longstanding efforts to address national needs in aeronautics and aviation.

In recent congressional testimony on the Next Generation Air Transportation System, whose acronym is NGATS, the GAO witness stated that "many experts told us that NASA's new focus on fundamental research creates a gap in the NGATS technology development continuum. The FAA's R&D Advisory Committee further estimated that establishing the necessary technology development infrastructure in the FAA could delay the implementation of NGATS by five years."

That concerns me, as does the statement by FAA's Aircraft Safety Advisory Subcommittee, which recently cautioned that "The Subcommittee on Aircraft Safety is concerned that there may be inadequate resources in the FAA's budget for taking on safety-related research that NASA used to perform in the past, but won't be funded to cover in the future."

And finally, there was testimony at the Science Committee's recent hearing on Homeland Security issues about R&D related to unmanned aerial vehicles, known as UAVs. Namely that "One might have expected NASA to pioneer in developing many of the technologies listed above, as UAVs have both military and commercial applications in addition to those of DHS. The UAV National Industry Team and the NASA ACCESS 5 Project were addressing the issues. With the reduction in the NASA aeronautics budget, ACCESS 5 was canceled and it appears this will not happen."

While I am sure that our NASA witness will make a good faith effort to put the best face on what is going on, I am deeply concerned that NASA's aeronautics program is, to use the word of a previous witness before this committee, on a path to being irrelevant to meeting our national needs. Now, I don't believe we have passed the point of no return, but we are getting close and the clock is ticking.

Let me close by once again reminding everyone of the policy statement contained in the *NASA Reauthorization Act of 2005.* "Congress reaffirms the national commitment to aeronautics research made at the *National Aeronautics and Space Act of 1958.* Aeronautics research and development remains a core mission of NASA. Further, the government of the United States shall promote aeronautics research and development that will expand the capacity, ensure the safety, and increase the efficiency of the Nation's air transportation system, promote the security of the Nation, protect the environment, and retain the leadership of the United States in global aviation."

If these are to be more than noble sentiments, Congress and the Administration together have a lot of work to do to get NASA's aeronautics program back on a healthy and productive path.

With that, I again want to welcome our witnesses and I look forward to their testimony.

[The prepared statement of Mr. Udall follows:]

PREPARED STATEMENT OF REPRESENTATIVE MARK UDALL

Good afternoon. I'd like to join Chairman Calvert in welcoming the witnesses to today's hearing. And I'd like to use my opening remarks to provide some context for today's hearing and explain why I think it is so important that we undertake some serious oversight in this area.

In short, I believe that ill-advised budget cuts and changes in NASA's priorities are putting the Nation at risk of losing critical aeronautics research and development capabilities. These are capabilities that we need now more than ever if we are to improve the safety and reliability of our air transportation system while at the same time increasing its capacity to meet projected demand, increasing its efficiency and performance, and reducing its environmental and energy impacts.

Moreover, those same aeronautics R&D capabilities have the potential to contribute to our national defense and the security of our homeland—as has been amply demonstrated in the past. Yet, instead of investing more in the highly productive aeronautics enterprise that has been built up within NASA and its predecessor organization over the last nine decades, NASA is in the process of *dismantling* those capabilities as it turns its attention elsewhere and reallocates resources to new ventures.

Because the budgetary erosion has been incremental, it is easy to underestimate the magnitude of the damage that is being done.

Perhaps the following statistics will help clarify the problem: In 1994, NASA spent more than **$1.8 billion** (in 2006 dollars) on aeronautics R&D. For FY 2007, on the other hand, NASA has requested just **$724 million**. . .or two and a half times less than the 1994 investment level.

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As Dr. Paul Kaminski, the Chair of the National Academies' Decadal Survey of Civil Aeronautics has warned: *"This budgetary trend will make it increasingly difficult for NASA to build a solid foundation for the future."*

Unfortunately, those budget cuts have been coupled to a restructuring of its aeronautics program that appears to be backing away from the highly productive partnership between government, industry, and academia that has long been the hallmark of NASA and its predecessor organization's aeronautics research programs. Instead, NASA has turned to a program more narrowly focused on fundamental research—the vast majority of which is to be carried out "in-house" by NASA.

While I applaud the strengthening of NASA's fundamental aeronautics research program—which had suffered in recent years due to the overall squeeze on NASA's aeronautics budget—that move unfortunately is coming at the expense of a broader vision of what NASA aeronautics R&D should be about.

Again, let me quote the words of several of the witnesses who testified at the July 18th hearing. . .

> For example, Dr. Stephen Merrill, of the National Academies committee on Innovation Models for Aeronautics Technologies has stated: *"The committee concluded that support of fundamental research is important but not sufficient to accomplish the Federal Government's legitimate role in advancing the air transportation system. There will remain a 'valley of death' between fundamental research results and systems innovation. Moreover, the support of technology users needed to sustain NASA's role in aeronautics will very likely continue to wane, undermining even its contributions to research."*
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However, my concerns extend beyond the lack of adequate participation by industry and academia in NASA's restructured aeronautics research program. They also go to my concerns that NASA's budgetary situation and its changed priorities are causing it reduce its commitment to long-standing efforts to address national needs in aeronautics and aviation.

In recent congressional testimony on the Next Generation Air Transportation System [NGATS], the GAO witness stated that: *". . .many experts told us that NASA's new focus on fundamental research creates a gap in the [NGATS] technology development continuum. . .REDAC [the FAA's R&D Advisory Committee] further estimated that establishing the necessary [technology development] infrastructure in FAA could delay the implementation of NGATS by five years."*

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Let me close by once again reminding everyone of the policy statement contained in the *NASA Authorization Act of 2005: "Congress reaffirms the national commitment to aeronautics research made in the National Aeronautics and Space Act of 1958. Aeronautics research and development remains a core mission of NASA. Further, the government of the United States shall promote aeronautics research and development that will expand the capacity, ensure the safety, and increase the efficiency of the Nation's air transportation system, promote the security of the Nation, protect the environment, and retain the leadership of the United States in global aviation."*

If those are to be more than noble sentiments, Congress and the Administration together have a lot of work to do to get NASA's aeronautics program back on a healthy and productive path.

With that, I again want to welcome our witnesses, and I look forward to their testimony.

Chairman CALVERT. I thank the gentleman. Without objection, the opening statements of other Members will be put in the record. Hearing no objection, so ordered. I would also ask unanimous consent to insert the appropriate place in the record other statements, as well as the background memorandum prepared by the majority staff for this hearing. Hearing no objection, so ordered.

[The prepared statement of Mr. Honda follows:]

PREPARED STATEMENT OF REPRESENTATIVE MICHAEL M. HONDA

Chairman Calvert and Ranking Member Udall, thank you for holding this important hearing today. I believe it is essential that, as NASA considers restructuring its aeronautics program, the important advice being provided by the National Research Council be taken into consideration.

Over the past several years, NASA has undertaken a series of significant overhauls of its aeronautics program, many of them without sufficient Congressional Oversight. In his FY 2006 Budget Request, President Bush tried to cut aeronautics programs over 21 percent by FY10, not counting the loss in purchase power due to inflation. Only the actions of the Congress prevented these drastic cuts from taking place.

The decisions NASA and the Administration are making seem to fly in the face of a number of recommendations made by expert panels. A RAND Corporation panel recommended that "of the 31 existing major NASA test facilities, 29 constitute the 'minimum set' of facilities important to retain and manage to serve national needs." A National Academies committee concluded that "although a strong national program of aeronautics research and technology [R&T] may not, by itself, ensure the competitiveness of the U.S. aviation industry, the committee agrees with earlier studies that without it, the United States is likely to become less competitive in aeronautics relative to countries with stronger programs. Aviation is an R&T-intensive

industry.. . .Some aeronautics R&T programs have produced 'breakthroughs' that are immediately usable.. . .More often, aeronautics R&T advances are evolutionary, and a substantial number of years can pass before the aviation systems making use of these advances enter service." This last statement is particularly interesting in light of the fact that NASA is currently saying that it is going to focus only on "breakthrough" technologies.

In the *NASA Authorization Act of 2005,* this committee recognized the short-sightedness of the Administration's plans to shut down key aeronautics test facilities and included language to keep these facilities open. Unfortunately, there are reports that as part of her restructuring of NASA's aeronautics program, the Associate Administrator is considering withdrawing support for facilities such as the "Future Flight Central" simulator, the Vertical Motion Simulator, and the Crew Vehicle Systems Research Facility at the NASA Ames Research Center. I question the wisdom of such actions and hope to hear the witnesses' thoughts on them.

NASA seems to be following a course on aeronautics that has potentially grave consequences not only for its Research Centers and those who work there, in particular the Ames Research Center near my district, but also for our nation. I hope that Dr. Porter will address my concerns in her testimony.

Chairman CALVERT. I would now like to introduce our first witness, Dr. Lisa Porter, NASA Associate Administrator for Aeronautics. Before I do so, I might remind Dr. Porter that as we requested in our authorization, we are looking forward to an aeronautics policy which is expected to be received in December. So I would hope that that is on a timely basis and that we will receive that document so we can review that this year.

Dr. PORTER. I believe you are referring to the National Aeronautics Policy, correct?

Chairman CALVERT. That is correct.

Dr. PORTER. Yes.

Chairman CALVERT. So we look forward to seeing that, and with that, you are recognized for 10 minutes.

STATEMENT OF DR. LISA J. PORTER, ASSOCIATE ADMINISTRATOR FOR AERONAUTICS, NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Dr. PORTER. Okay. Mr. Chairman and Members of the Subcommittee, thank you for this opportunity to appear before you today to present NASA's new aeronautics research program. Before I begin, I would like to first ask that my written statement and the accompanying programmatic fact sheets be entered for the record.

Chairman CALVERT. Without objection, so ordered.

Dr. PORTER. Thank you, Mr. Chairman.

During the past year, NASA's Aeronautics Research Mission Directorate, more commonly known as ARMD, has undergone a comprehensive restructuring to ensure that we pursue long-term cutting edge research that expands the boundaries of aeronautical knowledge for the benefit of the broad aeronautics community, which includes our partners in academia, industry, and other government agencies. For the American public, our research will contribute to a safer, more environmentally friendly and more efficient national air transportation system. At the same time, our research will continue to play a vital role in support of the vision for space exploration.

Our restructuring has been guided by three core principles. First, we will dedicate ourselves to the mastery and intellectual stewardship of the core competencies of aeronautics for the Nation in all flight regimes. Second, we will focus our research in areas that are appropriate to NASA's unique capabilities. And third, we will directly address the fundamental research needs of the Next Generation Air Transportation System, or NGATS, while working closely with our agency partners in the Joint Planning and Development Office, or JPDO.

Underlying all three principles is the fact that the most important part of NASA's aeronautics research is knowledge. Advanced technologies often result from an improvement in our knowledge and understanding. They represent an ability to apply the knowledge that we have gained, but so do computational tools, experimental methods, new scaling laws, and new design tools. If we do not focus our research on fundamental aeronautical challenges that will significantly advance our knowledge and understanding, any technology that is developed will look like everything that came before.

A focus on devices—rather than on the knowledge that enables them—leads to an emphasis on the wrong metrics to assess the quality of aeronautics research. Most notable among these is the Technology Readiness Level, or TRL. The TRL simply measures the level of maturity of a particular technology. It does not assess the value of the technology itself. One can develop a device to a very high TRL, but that in no way guarantees that it will successfully transition to the aeronautics community. Conversely, some of the most widely used products that have resulted from NASA's aeronautics research are items to which one cannot assign a TRL, such as technical reports, a whole host of computational tools, experimental techniques and methods, and aeronautical design concepts. All of these successfully transitioned to the user community and have been used broadly without the use of a TRL metric.

The correct question to ask, then, is not what is the appropriate TRL for NASA to establish as a goal to ensure successful transition of its technology, but rather, how do we ensure that the advances in knowledge, understanding, tools, concepts, methods and technologies developed at NASA transition smoothly and quickly to the broad aeronautics community?

We believe that we have implemented a process for restructuring that answers this question. Our approach was designed to ensure full and open access to information and opportunities for collaboration with NASA without providing any preferential access to any particular company or university. To that end, we used a request for information, or RFI, to solicit interest from industry for cooperative partnerships in pre-competitive research that would enable NASA to leverage industry's systems level expertise while facilitating the rapid transfer of knowledge and technology from NASA to industry. We received more than 230 responses from over 100 different organizations. NASA researchers at the research Centers then incorporated feedback from RFI respondents as well as from colleagues in other government agencies to develop detailed technical proposals which will be viewed by panels of subject matter experts from the DOD, the JPDO, the FAA, and NOAA, who evaluated the proposals based on a technical, management, resource, and partnership plans. This rigorous proposal review process ensured that we had technically credible and relevant research objectives and a sound approach for pursuing those objectives. It also allowed us to identify research areas where we needed to supplement our in-house capabilities with external expertise. We used a NASA research announcement, or NRA, as the means to solicit research proposals in those areas and competition for the NRA awards is full and open.

One of the key objectives of our NRA investment is to stimulate close collaboration among NASA researchers and NRA award recipients to ensure effective knowledge transfer. In the first evaluation round, we received more than 700 proposals from more than 110 universities and over 120 companies and non-profits. We hope to have awards in place by October and November of 2006.

Now that you have a better understanding about how we got to where we are today, I would like to now address four key topics that I believe are of particular interest to this committee.

First, I would like to address the issue of funding for aeronautics research. The fiscal year 2007 President's budget request of $724 million for ARMD provides the resources needed to support both programmatic requirements and institutional requirements. As outlined in an August 15, 2006 letter from Administrator Griffin to this committee, beginning in 2007 NASA plans to manage its Center overhead costs with a single rate for the non-federal Centers. This reallocation of Center overhead costs is a budget-neutral change, meaning that the total amount of funding going to each NASA Center is unchanged. The total amount of funding for direct program and project activity is unchanged. The total amount of funding for overhead is unchanged, and of course, the total NASA budget is unchanged.

The aeronautics top line budget will decrease by about $200 million under this overhead simplification approach, but that $200 million is not part of our direct research budget; it is part of the institutional funding that pays for the overhead costs of the research Centers, costs that will now be shared by all the mission directorates once the Agency's overhead budget as a whole is redistributed. The key point is that ARMD will still have the same research content in all of its research and projects as a result of this overhead accounting change, but we will no longer have to pay a large portion of the overhead costs for the research Centers.

Let me now turn to the second topic, the NRC Decadal Survey of Civil Aeronautics. Although it was sponsored by ARMD, it was conducted completely and independently of the restructuring activities occurring within ARMD, per the National Academy rules. That said, the 51 technical challenges and the five common themes identified in the report are closely aligned with our restructured research portfolio. However, we would like to clarify one issue raised in the report: the claim that ARMD spends 93 percent of its funds in-house. In reality, $180 million of NASA's fiscal year 2007 President's aeronautic budget request would pay for out-of-house activities to support our research programs. Note that $180 million is roughly one-third of our total budget under the simplified full cost accounting approach.

The third topic I would like to highlight is the great progress we are making in increasing and expanding our partnerships with research stakeholders. In addition to the great success of our NRA, we anticipate several space act agreements with industry that will enable us to work together in areas of pre-competitive research. Some of these potential partnerships are highlighted in the material that has been submitted for the record.

Another way that ARMD is reaching out to stakeholders is through meetings with intellectual leaders in industry and academia. My senior staff and I frequently travel to companies and universities across the country in order to interact with scientists, engineers, and managers who best understand the research challenges of the aeronautics community.

In addition to reaching out to industry and academic stakeholders, NASA is committed to expanding our partnerships with the DOD. On August 7, 2006, NASA signed a memorandum of understanding with the United States Air Force covering aeronautics research. Our partnership with the Air Force has its roots in some tremendous historical accomplishments, including several successful X-vehicle collaborations. Today, our partnership in X-vehicle research continues with the X–51 hypersonics program, and the X–48B blended-wing body program. But our partnership will extend beyond X-vehicles and will include cooperation and collaboration in many important areas of aeronautical research, including advanced aircraft design, advanced propulsion technology, advanced materials design, and advanced safety technologies.

NASA is also committed to working with its government partners in the JPDO. We have interacted closely with the JPDO during the past year to ensure proper alignment of our research plans with the needs of the NGATS. We solicited input from the JPDO during both our preliminary technical planning last fall and our rigorous proposal review process this past spring.

In addition to conducting research that directly addresses NGATS challenges, we have placed a strong emphasis on active participation in the JPDO, providing personnel, analysis tools, and funding to directly support its functions and activities. Regarding partnerships, it is important to note that our research will continue to play a vital role in the support for the vision of space exploration. Aeronautics research and space exploration are inextricably linked. The recent gap filler incident on the STS 114 shuttle flight served as a potent reminder that the first and last 100 miles of any journey from Earth to lower Earth orbit, to the Moon, or to Mars and back is through the Earth's atmosphere. We must also remember that the atmosphere of Mars presents a daunting challenge for safely landing large payloads; therefore, we will need to greatly advance our fundamental understanding in key aeronautics disciplines across all flight regimes, from subsonic through hypersonic, in order to advance our capabilities for safe flight through any atmosphere, be it our own or that of another planet.

Finally, while ARMD has spent much of this year in a planning and reorganization phase, each of our four programs has several exciting technical accomplishments to report, some of which are described in the programmatic fact sheets that were provided to you. I would like to take a moment to highlight just a few of them.

First, in our Airspace Systems Program, the future air traffic management concepts evaluation tool, or FACET, won NASA's Software of the Year Award in 2006. In the aeronautics test program, we have initiated test technology investments, including standardizing wind tunnel measurements systems across all the research Centers, and developing test facility control system simulators. In the Aviation Safety Program, the airborne subscale transport aircraft research test bed was completed and will support research and prevent in recovery and upsets and transport aircrafts. And finally, in the Fundamental Aeronautics Program, we pushed the high end of the flight envelope jointly with the Air Force through the Mach 5 ground testing of a thermally stable advanced hydrocarbon field scram jet.

In conclusion, NASA's aeronautics research will advance the frontiers of flight for the benefit of the Nation's civilian, federal, and military communities. NASA's restructured program ensures long-term focus on fundamental research in both traditional aeronautics disciplines and relevant emerging fields that can be integrated into multi-disciplinary system of capabilities that can be broadly applied. This approach will enable revolutionary advances in both the airspace system and the aircraft that fly within it.

Once again, thank you for the opportunity to testify today. I would be pleased to answer any questions that you may have.

[The prepared statement of Dr. Porter follows:]

PREPARED STATEMENT OF LISA J. PORTER

Mr. Chairman and Members of the Subcommittee, thank you for this opportunity to appear before you today to present NASA's new aeronautics research program. During the past year, NASA's Aeronautics Research Mission Directorate (ARMD) has undergone a comprehensive restructuring to ensure that we have a strategic plan in place that enables us to pursue long-term, cutting-edge research for the benefit of the broad aeronautics community.

Today, NASA's aeronautics research programs are positioned better than ever to provide meaningful and relevant research that is aligned with our National priorities. We are conducting high-quality, innovative, integrated research across the fundamental disciplines of aeronautics, creating revolutionary tools, concepts, and technologies that will lead to a safer, more environmentally friendly, and more efficient national air transportation system. At the same time, we are ensuring that aeronautics research and critical core competencies continue to play a vital role in support of the Vision for Space Exploration. Lastly, NASA's refocused aeronautics program is establishing strong partnerships with academia, industry and other Government agencies, and in doing so, we are ensuring that our world-class resources are readily available to them.

Guiding Principles

In restructuring NASA's aeronautics program, we were guided by three core principles: 1) we will dedicate ourselves to the mastery and intellectual stewardship of the core competencies of aeronautics for the Nation in all flight regimes; 2) we will focus our research in areas that are appropriate to NASA's unique capabilities; and, 3) we will directly address the fundamental research needs of the Next Generation Air Transportation System (NGATS) while working closely with our agency partners in the Joint Planning and Development Office (JPDO). It is important to emphasize that these principles are budget-independent, as they must be, in order to ensure consistency and stability of programmatic decisions over the long-term.

Given the critical importance of these principles, I take the time here to elaborate on each in more detail, beginning with the first. NASA's ARMD does not have an operational mission. We do not build aircraft to defend our Nation or to sell in the commercial marketplace. We are not responsible for implementing the national air transportation system, nor do we build robotic and human spacecraft. Our role is to provide the wellspring of aeronautical knowledge for our partners in both the Government and private sector who are responsible for these missions. Therefore, we must and will pursue long-term, cutting-edge research in the core aeronautics disciplines across all flight regimes, in order to enable the quantum leaps in knowledge that lead to the development of revolutionary ideas, concepts, approaches, technologies, and capabilities that have broad applicability.

Regarding the second principle, we will not duplicate research being conducted in other agencies, nor will we conduct research that is the responsibility of other agencies. Furthermore, we will not conduct research that is more appropriately conducted in the private sector. Specifically, we will not conduct near-term, incremental research, nor will we conduct research that benefits only a small subset of industry. Our research will be pre-competitive, cutting-edge, and will benefit the community broadly. To that end, we intend to publish our research results to the greatest extent practicable in as timely a manner as possible.

The third principle speaks to our commitment to the NGATS vision as articulated by the JPDO. Here, it is important to realize that while Air Traffic Management (ATM) research is a vital component of the fundamental research that we will conduct in support of the NGATS vision, our commitment must and will extend beyond ATM research. Increasing the capacity of the ATM system by factors of two or three will be nothing more than a theoretical exercise if we do not simultaneously address the substantial noise, emissions, efficiency, safety, and performance challenges facing the air vehicles of the future. These are issues that cannot be worked in isolation—a holistic approach to vehicle design will be required in order to address multiple and often conflicting design requirements.

Given these three principles, we then established the four programs within ARMD: the Fundamental Aeronautics Program; the Aviation Safety Program; the Airspace Systems Program; and the Aeronautics Test Program. The Fundamental Aeronautics Program conducts cutting-edge research that produces concepts, tools, and technologies that enable the design of vehicles that fly through any atmosphere at any speed. The Aviation Safety Program is focused on developing revolutionary tools, methods, and technologies that will improve the inherent safety attributes of current and future aircraft that will be operating in the evolving National Airspace System (NAS). The Airspace Systems Program is directly addressing the fundamental ATM research needs of the NGATS. This research will yield revolutionary concepts, capabilities, and technologies that will enable significant increases in the capacity, efficiency and flexibility of the NAS. The Aeronautics Test Program is ensuring the strategic availability and accessibility of a critical suite of aeronautics test facilities that are necessary to meet aeronautics, Agency, and National needs.

While each program focuses on a particular aspect of aeronautics research, the four programs interact closely with one another starting with the researchers at the NASA Research Centers all the way up the programmatic chain to Headquarters. A detailed summary of each program is provided in the supplementary material, which includes program and project overviews, key accomplishments in FY 2006, and partnerships that have been established or that are being developed with industry and other government agencies.

From Strategic Vision to Implementation: Details About Our Process

ARMD established a four-step approach to putting together technical plans in the ten aeronautics projects in our four aeronautics programs. The approach was designed to enable us to foster close collaboration with and to facilitate the exchange of ideas and information among researchers at NASA, industry, academia, and other government agencies, in a manner that benefits the community broadly.

Last fall, we completed the first step, during which researchers at the four research Centers came together to develop preliminary ten-year roadmaps that included technical milestones for each project in each program. These roadmaps were vetted with our Government partners in the Department of Defense (DOD), Federal Aviation Administration (FAA), and JPDO in late 2005, and were then presented to the broad aeronautics community at the American Institute of Aeronautics and Astronautics conference in January 2006, while simultaneously being posted to our web site. Our intent was to ensure full and open access to information, without providing any preferential access to particular companies or universities.

In January 2006, we began our second step by releasing a Request for Information (RFI), soliciting interest from industry for non-reimbursable cooperative partnerships in pre-competitive research that would allow NASA to leverage industry's systems-level expertise while facilitating the rapid transfer of knowledge and technology from NASA to industry. We received more than 230 responses from over 100 different organizations, many of which have already resulted in working collaborations.

Our third step was the internal proposal process. Using the preliminary roadmaps as a starting point, NASA researchers incorporated feedback from RFI respondents as well as from colleagues in other government agencies to develop refined technical proposals for each project. These proposals were then reviewed by panels of Government subject matter experts from the DOD, JPDO, FAA, and the National Oceanic and Atmospheric Administration. Proposals were evaluated based on their technical, management, resource, and partnership plans. Simultaneously, the management at the four NASA research centers conducted their own independent review of each proposal. Researchers were then provided detailed feedback from both reviews and used that feedback to further refine their proposals, which then underwent a second peer-review at NASA Headquarters. This rigorous proposal review process ensured that we had technically credible and relevant research objectives and a sound approach for pursuing these objectives. It also allowed us to identify foundational research areas where we needed to supplement our in-house capabilities with external expertise.

During the fourth and final step, we released a NASA Research Announcement (NRA) to solicit proposals from the external community in foundational research areas where NASA needs to enhance its core capabilities. NRA competition was full and open. One of the key objectives of our NRA investment is to stimulate close collaboration among NASA researchers and NRA award recipients to ensure effective knowledge transfer. The first round of proposals closed July 7, 2006. We are very pleased with the number and quality of proposals received and the diversity of submitting organizations. In the first evaluation round, we received more than 700 proposals from more than 110 universities and over 120 other organizations (companies and non-profits). More than 600 highly qualified technical and scientific experts from NASA and other organizations provided thorough reviews of these proposals. We hope to have awards in place by October and November 2006. Additionally, the NRA will remain open to enable us to conduct another round of proposal evaluations.

In summary, ARMD has sought input from all aeronautics stakeholders during its reorganization process, and we did so in a manner that did not provide preferential access to information or opportunities for collaboration to any particular company or university. Our research is paid for by the American public, and therefore we are obligated to provide aeronautics research that benefits the community broadly. Narrowing our research focus to the needs of a small subset of companies runs counter to our mission and counter to the Nation's best interests. Therefore, we are actively seeking participation from all aeronautics stakeholders during our restructuring and are establishing close collaborations with both large and small companies.

Aeronautics and Space Exploration

I would like to directly address the misperception by some individuals who believe that support for the *Vision for Space Exploration* has resulted in a decline in the Agency's commitment to aeronautics research. Quite the contrary, aeronautics research has a critical role to play in the Vision.

Aeronautics research and space exploration are inextricably linked. The X–15 program provides a great historical example of the essential contributions that aeronautics research has made to our nation's successful space exploration activities. By contrast, the recent gap-filler incident on STS–114 shows what happens when aeronautics research fails to provide the fundamental knowledge and understanding needed to address emergent issues across all flight regimes. When the concern arose whether high speed air flowing over a protruding "gap filler" on the Shuttle could cause excessive heating during re-entry, we did not have sufficient data or analysis capability to provide a timely, decisive answer. As such, we were forced to conduct an unplanned and somewhat risky space walk to remove the gap filler.

Our future space exploration efforts are critically dependent upon advancing our state of knowledge in aeronautics. The STS–114 Shuttle flight served as a potent reminder that the first and last 100 miles of any journey from Earth to lower-Earth orbit, the Moon, or Mars and back is through the Earth's atmosphere. We must also remember that the atmosphere of Mars is approximately 60 miles thick, and its properties present a daunting challenge for safely landing large payloads. It is thick enough to cause severe heating challenges but thin enough to make deceleration extremely difficult. Therefore, we will need to greatly advance our fundamental understanding in key aeronautics disciplines such as aerodynamics, aerothermodynamics, materials, and structures, across all flight regimes from subsonic through hypersonic, in order to advance our capabilities for safe flight through any atmosphere, be it our own, or that of another planet.

NASA Discusses Issues Raised During July 18th House Aeronautics Subcommittee Hearing

On July 18, 2006, Members of this committee held the first of two hearings about NASA's efforts to reshape its aeronautics research and development program. I was unable to testify at that hearing, but am happy to be here today to address some of the issues and concerns raised by witnesses and Members during that first hearing.

Today, there are four key topics of concern to the Committee that I would like to address, the first of which is the National Research Council's *Decadal Survey of Civil Aeronautics.*

1) The Decadal Survey of Civil Aeronautics

Although the *Decadal Survey of Civil Aeronautics* was sponsored by ARMD, it was conducted completely independently of the restructuring activities occurring within ARMD. That said, the 51 Technical Challenges and five Common Themes identified in the report are closely aligned with ARMD's restructured research portfolio. For example, the common themes of physics-based analysis tools and multi-disciplinary design tools are present across all of our projects. We strongly agree with the report's findings that state that "an important benefit of advances in physics-based analysis tools is the new technology and systems frontiers they open. New concepts often emerge from a greater understanding of the underlying physics offered by new analytical capabilities. NASA, industry, and academia can jointly participate in research into physics-based analysis tools because it is fundamental in nature, publishable, and sharable. This research will take time to mature, yet advances can readily be translated into practice as they occur." We also strongly agree with their comments regarding multi-disciplinary design tools: "The next step in the design of more complex systems involves more than just. . .gluing together discipline-specific analyses and optimization. New multi-disciplinary tools are needed to integrate high-fidelity analyses with efficient design methods and to accommodate uncertainty, multiple objectives, and large-scale systems. . .."

Regarding the theme of advanced configurations, we agree that the pursuit of advanced configurations, such as revolutionary aircraft concepts and advanced structural designs, can foster the implementation of innovative solutions to systems-level challenges. In fact, across our research portfolio, our focus on physics-based, multi-disciplinary design, analysis, and optimization tools with quantified levels of uncertainty will enable virtual expeditions through design space in order to identify advanced configurations that have the greatest possibility of meeting multiple and often conflicting system-level requirements. Regarding the intelligent and adaptive systems theme, which "encompasses aircraft-level challenges aimed at sensing the operational environment, actively responding to that environment, and learning from the resulting interactions," our Aviation Safety Program also embraces this as an important theme. Finally, we agree that the "air transportation system must be understood as a complex interactive system," and we agree with each of the systems issues identified under that theme, and with the cautionary statement that "system models typically examine isolated effects or components within the system, and few models attempt to examine a large range of complex, interactive system effects, especially those involving non-deterministic behaviors."

However, we would like to clarify one issue raised in the report—the claim that ARMD spends 93 percent of its funds in-house, implying that 93 percent of our funds pay for civil servants. In reality, $180 million of NASA's FY 2007 aeronautics budget request would pay for out-of-house to support our research programs. Of that total, about $50 million would pay for research awarded under the NRA. The remainder of the out-of-house dollars, about $130 million, would pay for on-site research contractors (contracts are competitively awarded), hardware/software procurements, wind tunnel fabrications, JPDO procurement funds and HQ studies such as the Decadal Survey. None of the $180 million would pay for NASA civil servants.

Lastly, I would like to reiterate that NASA intends to fully comply with a statutory requirement to conduct two National Research Council studies by Dec. 31, 2007.

2) Fundamental research vs. demonstration projects

The second topic I would like to address is NASA's decision to focus on fundamental aeronautics research instead of point-design demonstration projects. There are three points I would like to make regarding this topic:

First, it is important to understand that aircraft design is perhaps the ultimate art of compromise. Every aircraft is an integrated system representing a balance and compromise between conflicting requirements: it is a lesson as old as the Wright brothers. Indeed, the modern discipline of system engineering has its roots in the design of aerospace vehicles. Since aircraft of the future must continue to address multiple and usually conflicting design challenges such as noise reduction, emissions, fuel efficiency, and performance, addressing any one independently of the others will lead to partial solutions at best, and at worst, solutions that are misleading or ineffective. For example, focusing a significant amount of investment on a large-scale demonstration to "reduce noise by 50 percent relative to what the state-of-the-art was in 1997" (a demonstration project that was proposed in early 2005) will almost certainly yield solutions that are optimized for noise reduction at the expense of other critical system attributes. Reducing noise at the expense of performance or fuel efficiency, for example, is unlikely to provide a viable economic alternative to existing approaches. Revolutionary improvements in the capabilities of future aircraft must incorporate an integrated approach to aircraft design, which in turn necessitates a commitment to research that cuts across multiple disciplines such as aerodynamics, combustion, acoustics, materials, and flight controls.

Second, it is critical to understand that a demonstration is not an experiment. A demonstration sets out to prove that something works. An experiment, in contrast, sets out to pursue technical truth. These are very different goals. In a school setting, for example a high school or college physics or chemistry class, a demonstration can be extremely useful to teach students an already known truth. But this is a very different matter than undertaking fundamental research, where we are dealing not with knowns, but with unknowns-in short, the "X factor" that is inherent in the X series that have taken this nation from subsonic airplanes to hypersonic craft operating into space. Every airplane flying today demonstrates the basic principles of flight. But every day, at NASA's research centers, we are advancing our comprehension of those principles by probing the unknown via the scientific method. This is more than mere semantics; it is the fundamental thing that sets a research program apart from a demonstration. And there is another danger as well. If we think we already know the answer to a question, and we set out to prove that we are right, then we have forfeited our objectivity and have become advocates for a particular approach or technology. NASA's aeronautics programs must be conducted so as to provide objective and unbiased assessments, and such objectivity is compromised once one defines "success" as being "right." In the 1930's everyone "knew" the answer to future propulsion needs: bigger and better piston engines. Many advances in the state of the art for such engines were demonstrated. But it was in Britain and Germany where the next crucial steps in aviation were taken, through experiments with—not demonstrations of—jet and rocket engines. We must never find ourselves in such a position again.

Let us explore the implications of such thinking in today's world. Let's say, for example, that our research leads us to the discovery of a new concept for a device that we estimate could reduce the noise output from an engine by 20 percent. A demonstration (whether on the ground or in the air) would be designed to prove that the device does indeed reduce noise output by at least 20 percent. In other words, advocacy for the device becomes the goal of the demonstration and proof that the device works as predicted becomes the metric for success. There would be a limited number of runs, and the parameters would be chosen to ensure a high probability that the device meets or exceeds predicted performance. However, even if the demonstration is a "success," the results will have limited applicability, because it is just as important to know when the device fails to perform, and to try to understand why, in order to be able to use it effectively. But failure of the device runs counter to the objectives of a demonstration.

An experiment, on the other hand, would be designed to test the device across as broad a test regime as possible and to make careful measurements, with quantifiable error bars, to characterize its performance as fully as possible. The device would not be required to reduce noise output by 20 percent in order for the experiment to be considered a success, because the goal of the experiment is truth. Rather, the results would be useful to the broad community because the data would enable the entire community to understand the capabilities and limitations of the device, whatever they may be.

Third, some critics have assumed that NASA's decision not to expend our resources on large-scale point-design demonstrations equates to turning away from X-vehicle research. This criticism is based on a misunderstanding of what X-vehicles are designed to do. X-vehicles are not demonstrators; they are research aircraft. They were originally developed as research tools, with the sky as a laboratory. For example, the first X-vehicle, the X–1, was the result of a NACA/Air Force partnership that produced the first high-speed aircraft built solely for aviation research purposes. That it was not a mere demonstrator is evidenced by one of its design requirements: the plane carried hundreds of pounds of research instrumentation, including real-time telemetry, so that researchers could unlock the secrets of transonic and supersonic flight. All told, 157 test flights were conducted during the original X–1 program, and the knowledge generated from those flights was instrumental in enabling us to design supersonic fighter jets and transonic jet airliners alike. The X–15 program, which was a NACA/NASA, Air Force, and Navy partnership, performed 199 test flights and yielded over 750 technical publications. The knowledge produced by the X–15 program was critical in the development of re-entry and launch vehicles, including the Space Shuttle. Contrary to what some have claimed, NASA sees great value in X-vehicles, and anticipates continuing such partnerships with the DOD. For example, NASA is currently partnering with the DOD on the X–51 hypersonics program—a program that is building upon the results from the X–43A program. Ground testing of the X–51 engine will begin at NASA's Langley Research Center later this year, and flight tests are scheduled to begin in 2008.

The recent focus by some on demonstrations that prove technologies rather than experiments that expand the boundaries of aeronautical knowledge can be linked to the fact that some in the community have forgotten that the most important product of NASA's aeronautics research is knowledge. Advanced technologies often result from an improvement in our knowledge and understanding; they represent an ability to apply the knowledge that we have gained. But so do computational tools, experimental methods, new scaling laws, and new design tools. A focus on devices rather than on the knowledge that enables them leads to an emphasis on the wrong metrics to assess the quality of aeronautics research. Most notable among these is the "Technology Readiness Level," or TRL.

The TRL simply measures the level of maturity of a particular technology. It does not assess the value of the technology itself. One can develop a device to a very high TRL, but that in no way guarantees that it will successfully transition to industry. Conversely, some of the most widely used "products" that have resulted from NACA/NASA's aeronautics research are items to which one cannot assign a TRL, such as NACA technical reports, computational tools such as OVERFLOW, CFL3D, NASTRAN, and ACES, experimental techniques and methods, and aeronautical design concepts such as the transonic and supersonic area rules. All of these successfully transitioned to the user community and have been used broadly without the use of a TRL metric.

The correct question to ask, then, is not "What is the appropriate TRL for NASA to establish as a goal for technology development to ensure successful transition of its technology?" but rather "How do we ensure that the advances in knowledge, understanding, tools, methods, and technologies developed at NASA transition smoothly and quickly to the broad aeronautics community?" As outlined above, ARMD has developed a comprehensive, four-step approach that we think answers this question.

Finally, there are some who focus on TRLs because they believe that NASA should be required to provide sufficient investment in order to ensure that innovative technologies are developed to a high-enough maturity level so as to guarantee that industry can take them over with minimal risk. We note here what the Commission on the Future of the U.S. Aerospace Industry (2002) stated:

> *"Industry has the responsibility for leveraging government and university research and for transforming it into new products and services, quickly and affordably. But, the U.S. aerospace industry has not invested sufficiently to transition research into marketable products and services."*
>
> *"The Commission believes that the U.S. aerospace industry must take the leadership role in transitioning research into products and services for the Nation and the world. To assist them, the government must provide industry with insight into its long-term research goals and programs. With this information, the industry needs to develop business strategies that can incorporate this research into new products and services. Industry also needs to provide an input to the government on its research priorities."*

We at NASA believe that our restructured aeronautics program is well aligned with these recommendations. We intend to pursue long-term, cutting-edge research in the core aeronautics disciplines across all flight regimes, in order to enable the quantum leaps in knowledge that lead to the development of revolutionary ideas, concepts, approaches, technologies and capabilities that have broad applicability to the aeronautics community. Such research is appropriate for NASA to conduct, because the pay-off from an economic standpoint is typically uncertain as well as long-term, and the results are not appropriable to a single company.

Ultimately, however, it is up to each company to decide for itself whether to invest in the development of particular concepts and technologies. Removing most or all of the risk for industry to do that removes the influence of market economics. This is indeed a significant distinction between us and other countries. We believe that the free market is the best determination of what technologies should be developed for commercial application, not the government.

The bottom line is that if we do not focus our research on fundamental aeronautical challenges that will significantly advance our knowledge and understanding, any technology that is developed will look like everything that came before. And large-scale demonstrations that "prove" that such technologies "work" are the surest way to render NASA's aeronautics research program irrelevant.

3) Expanding academic, industry and Government partnerships

The third topic I will address is ARMD's determination to foster close collaboration with researchers at NASA, industry, academia, and other Government agencies in a manner that benefits the aeronautics community broadly. While ARMD has spent much of this year in a planning and reorganization phase, I can report that we are beginning to see the fruits of our labor pay off, particularly in the area of increased and expanded partnerships with research stakeholders. There are several ways in which NASA is reaching out to other aeronautics stakeholders. As outlined above, the RFI and NRA processes are the first way in which we are doing this.

Another way that ARMD is reaching out to stakeholders is through meetings with intellectual leaders in industry and academia. My senior staff and I frequently travel to companies and universities across the country in order to interact with scientists, engineers, and managers who best understand the research challenges of the aeronautics community. Since October 2005, my staff and I have met with more than 30 aeronautics companies, including several visits at company facilities across the country. We have several more such visits planned for this coming year.

ARMD has also begun a series of informal meetings with the aeronautics community that it intends to hold on a regular basis in order to maintain open lines of communication. It is anticipated that aeronautics leaders from industry, academia, industry associations, and non-profit associations will make up the pool of participants for the meetings, with the particular meeting topics determining the make-up of the meeting attendees. These meetings are not intended to generate definitive or consensus recommendations, but to provide participants with a forum to express their various individual points of view as experts in their field.

In addition, ARMD's research programs are using Industry Days as an effective means to reach out to our industry stakeholders. Industry Days are a useful means for industry participants to discuss the particulars of potential pre-competitive research partnerships appropriate for work under Space Act Agreements. The Aviation Safety Program, for example, recently hosted an industry day that drew around 100 participants representing about 25 companies as well as the FAA.

In addition to reaching out to industry stakeholders, NASA is committed to expanding our partnerships with the DOD. On August 7, 2006, NASA signed a Memorandum of Understanding with the U.S. Air Force, making it explicitly clear that we are committed to a partnership that has its roots in some of the greatest aeronautical accomplishments in world history.

Our historical accomplishments include several successful X-vehicle collaborations, including the X–1 and the X–15 mentioned above. Today, our partnership in X-vehicle research continues with the X–51 hypersonics program and the X–48B Blended Wing Body program. We anticipate other opportunities for collaboration on X-vehicle research in the coming months and years.

But NASA's partnership with the Air Force will extend beyond X-vehicles and will include cooperation and collaboration in many important areas of aeronautical research. Clearly, our missions are different and distinct, and neither of us has any intention of performing the other's mission. But we are united in the common goal of the pursuit of the frontiers of flight, and it is in the best interests of the Nation for us to leverage each other's strengths and work together to continue the heritage of remarkable aeronautical achievements that this country has realized. Our collaborations will span all flight regimes from subsonic to hypersonic flight, and will advance our country's mastery of many of the critical elements of aeronautics, including advanced aircraft design, advanced propulsion technology, advanced materials design, and advanced safety technologies, such as resilient aircraft control methods and the ability to detect, predict, and mitigate the aging of aircraft components and systems. We will also work together to ensure that the Nation sustains a critical set of aeronautical research and test facilities.

Finally, NASA is committed to working with its government partners at the JPDO to provide the high-quality, cutting-edge research and technical excellence required to develop the NGATS. Here, we are building on a long history of collaboration with the FAA.

ARMD has interacted closely with the JPDO during the past several months to ensure proper alignment of our research plans with the needs of the NGATS. Specifically, we have solicited input from the JPDO during both our preliminary technical planning last fall and our rigorous proposal review process this past spring. Our thorough proposal review process ensured that the plans were technically credible and well-aligned with the NGATS vision. This level of coordination and cooperation will remain an ongoing element of the ARMD strategic partnership with the

JPDO. In addition to conducting research that directly addresses NGATS challenges, we have placed a strong emphasis on active participation in the JPDO, providing personnel, analysis tools, and funding to directly support its functions and activities. NASA is actively involved in all the organizational elements of the JPDO, from the Integrated Product Teams and the Evaluation and Analysis Division up through the Senior Policy Committee, which oversees the work of the JPDO and is chaired by the Secretary of Transportation.

4) Aeronautics funding

Finally, I would like to address the issue of funding for aeronautics research. The FY 2007 President's Budget Request of $724 million for ARMD provides the resources needed to support both institutional requirements and programmatic requirements. Institutional requirements include corporate and center general and administrative costs, and service pools to fund several key functions at the field centers. Programmatic costs support the direct activities for the four programs in this new plan.

As outlined in an August 15, 2006 letter from Administrator Griffin to the Committee, beginning in 2007, NASA plans to manage its Center overhead costs with a single rate for nine Federal Centers. This is a reallocation of Center overhead costs results in full-cost budget changes to all programs and projects and top-line changes to all Mission Directorates. This is a budget-neutral change. The amount of funding going to each research Center is unchanged; the amount of funding for direct program and project activity is unchanged; the total amount of funding for overhead is unchanged; as is the total NASA budget.

ARMD's overall budget will decrease by about $200 million under the overhead cost simplification system. But let me be clear, that $200 million was never used for research; it was always set aside to pay the overhead costs of the four research Centers—costs that will now be shared by all the mission directorates once the Agency's overhead budget as a whole is redistributed. ARMD will still have the same direct buying power. We also will no longer have to pay a large portion of the overhead costs for the four research Centers—Langley, Glenn, Ames and Dryden. The change also puts the research Centers on equal footing with the operational Centers and recognizes them as critical Agency assets, with the Agency itself being held responsible for the health of all ten Centers. Furthermore, the change will enhance transparency of Center expenditures, resulting in improved execution of ARMD programs.

Looking Toward the Future

NASA is excited about the significant milestones in the Nation's aeronautics program that will occur this fall, not only in NASA's aeronautics programs, but also in the U.S. aeronautics community as a whole.

First, NASA looks forward to the JPDO's public release of the Enterprise Architecture for NGATS in the near future. We will use this architecture as an additional means to ensure that our aeronautics research programs continue to contribute to the research needs of the Nation's future air transportation system. We also look forward to the Administration's release of the new National Aeronautics Policy in December.

For our part, ARMD hopes to have the first round of NRAs awarded by October through November of 2006. Additionally, the NRA will remain open to enable us to conduct another round of proposal evaluations. ARMD also anticipates finalizing several partnerships with industry through Space Act Agreements. Details regarding established and planned partnerships for each program can be found in the supplementary material. We also anticipate the completion of several technical milestones in many of our projects in the coming weeks and months, such as the testing of the X–51 engine in Langley's 8-foot tunnel, the Critical Design Review of the Hypersonics Boundary Layer Transition Experiment (HyBOLT) with ATK, new techniques for automatically analyzing large amounts of data to detect unsafe trends in a timely manner, and the completion of the Airborne Subscale Transport Aircraft Research (AirSTAR) test bed, which is a subscale fully functioning aircraft that supports research in upset modeling, prevention, and recovery of transport category aircraft.

Lastly, to better meet NASA's mission, ARMD is taking an active role in developing a workforce that will help retain the United States' leadership in aeronautics and astronautics. ARMD sponsored a workshop on June 1, 2006 to explore what can be done to improve the technical capabilities of a workforce to meet the needs of both NASA and the aerospace industry. Workshop participants from government, industry, academia, and professional and industry organizations discussed the future of higher education, and what can be done to better define and fill any gaps in the current education system that might prevent students from pursuing aerospace and aerospace-related careers. Outcomes of the workshop included a number of ideas and concepts, both near-term and long-term, about how we can all work together to improve the size and capability of the future technical workforce.

Following the workshop, ARMD redefined a number of its educational activities to better align with ongoing activities within universities, industry, and outside organizations. ARMD is partnering with these outside organizations by providing technical expertise to help train and educate the future aerospace workforce. These partnering activities include a series of case studies or lessons-learned monographs on aeronautical topics; expansion of its "Beginner's Guide to Aeronautics" Web-based learning to include an updated module on the hypersonic regime; a series of university texts and supplemental materials to fill gaps in the current educational background of university students; support of design competitions that provide university students with hands-on experience in the design and testing of aerospace systems; and better methods for communicating NASA's educational and research opportunities to stakeholders.

Concluding Remarks

ARMD's restructuring has resulted in a total of ten research projects distributed across three programs, as well as a separate program dedicated to the preservation of our key aeronautics test facilities. In order to ensure that our commitment to technical excellence is maintained, we intend to: 1) Provide the details of the technical content of each of our projects on our web site; 2) Publish our research results in peer-reviewed journals and NASA Technical Reports; 3) Establish technical working groups within each project to engage industry and academic partners on a regular basis in order to facilitate knowledge transfer; and 4) Conduct annual assessments of our portfolio with the assistance of subject matter experts.

NASA's aeronautics research will advance the frontiers of flight for the benefit of the Nation's civilian, federal, and military communities. In recent years, the emphasis on near-term, product-focused technologies shifted NASA's focus from long-term, cutting-edge research to incremental technology development and "point solutions" to complex challenges. NASA's restructured program ensures long-term focus in fundamental research in both traditional aeronautical disciplines and relevant emerging fields that can be integrated into multi-disciplinary system-level capabilities that can be broadly applied. This approach will enable revolutionary change to both the airspace system and the aircraft that fly within it, leading to a safer, more environmentally friendly, and more efficient national air transportation system.

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FUNDAMENTAL AERONAUTICS PROGRAM

The Fundamental Aeronautics program supports state-of-the-art research in tools and technologies that enable the design of vehicles that fly through any atmosphere at any speed. In particular, physics-based, multidisciplinary design, analysis, and optimization (MDAO) tools will make it possible to evaluate radically new vehicle designs and to assess, with known uncertainties, the potential impact of innovative technologies and concepts on the overall vehicle performance and value. The development of such tools requires a firm commitment to the pursuit of long-term, cutting-edge, integrated research across the core disciplines of Aeronautics. In addition to these system-level goals, advanced component technologies are being developed to realize the revolutionary improvements in noise, emissions, and performance that are required to sustain a viable future air transportation system. The Fundamental Aeronautics program also helps advance the Agency's human and robotic exploration missions by creating tools that support the development of planetary atmospheric entry vehicles and that facilitate access to space. The Fundamental Aeronautics program is comprised of four projects:

Fixed Wing: This project addresses the requirement that future transport aircraft need to be quieter and cleaner to meet demanding constraints in noise and emissions. At the same time, these aircraft must meet challenging performance requirements to make them economically viable alternatives to the existing fleet. Foundational research in core disciplines will be integrated to enable significant advances in propulsion-power systems, vehicle systems integration and analysis, airframe systems, and systems for experimental validation. Validated, physics-based MDAO capabilities will enable predictive design of a wide class of air vehicles that will meet the future performance challenges for both civilian and military applications.

Rotary Wing: This project focuses on removing the technical barriers that constrain rotorcraft from reaching widespread use in civil aviation. These barriers include range, speed, payload capacity, fuel efficiency, and environmental acceptance (noise in particular). Foundational research in core disciplines will be integrated to enable significant advances in propulsion-aeromechanics integration, integrated vehicle management systems, integrated rotorcraft design, and innovative experimental methodologies. Validated, physics-based MDAO tools will enable predictive design of advanced capability rotorcraft that meet noise and performance challenges.

Supersonics: The Supersonics project has two basic objectives. The first one is the elimination of the efficiency, environmental and performance barriers to practical supersonic cruise in the Earth's atmosphere. The other is to address the critical issue of supersonic deceleration to enable safe, precision planetary entry, descent, and landing of human and large scientific missions in any atmosphere. Foundational research in core disciplines will be integrated to enable significant advances in aircraft systems integration and analysis, airframe systems, propulsion-power systems, and integrated system-level experimental validation. Validated, physics-based MDAO capabilities will enable system-level design of supersonic vehicles that will meet the emission, noise, sonic boom, and performance challenges of the future. In addition, advanced analytical capabilities will enable lightweight concepts for precise, controllable supersonic descent through planetary atmospheres.

Hypersonics: All access to space, either suborbital or in Earth orbit, and all entry from space through any planetary atmosphere, requires hypersonic flight. In order to continue to advance our capabilities for flight in these regimes, improved understanding of hypersonic phenomena is needed. Improved technologies to withstand and take advantage of the high temperature environment are also required. Foundational research will be conducted to enable significant advances in high-speed aerodynamics, very high temperature materials and structures, and robust flight controls. Validated physics-based MDAO capabilities will reduce uncertainties and risk, increase performance, and enable new vehicle concepts. Furthermore, our increased knowledge of hypersonic systems will pave the way for new vehicle architectures to increase the reliability of launch and improve the performance of entry vehicles.

Fundamental Aeronautics Program's Recent Accomplishments

Fixed Wing Project

- Tested two Blended Wing Body (BWB) models to investigate the potential of this revolutionary aircraft configuration to significantly reduce noise and emissions while improving overall performance. A BWB 8.5 percent model was tested in the Langley Research Center full-scale tunnel and a two-percent model was tested in the National Transonic Facility to characterize the aerodynamic and control characteristics in preparation for flight tests at Dryden in early 2007. This work supports X-48B flight test opportunities planned in FY07.
- Completed the design of geared turbofan components in collaboration with Pratt & Whitney. Studies conducted by NASA and Pratt & Whitney identified a low fan-pressure-ratio geared turbofan design with a lightweight Variable Area Fan Nozzle as an attractive approach to reduce both noise and emissions relative to the current state-of-the-art. The design for a geared turbofan engine was completed. Testing of a model fan in the Glenn Research Center 9X15 wind tunnel started in September 2006.

Rotary Wing Project

- Conducted helicopter flight tests to provide data for validation and improvement of rotorcraft acoustic analysis tools and to develop low noise flight profiles. The test was jointly executed by NASA, the U.S. Army, the Center for Rotorcraft Innovation, Bell Helicopter, and the University of Maryland. Test results will be used to test advanced prediction models.

Supersonics Project

- Under an interagency agreement with the Federal Aviation Administration (FAA), the Supersonics Project began a study of material and structural concepts for advanced fan containment systems applicable to both subsonic and supersonic aircraft. Initial material procurement and test article manufacturing is underway with testing to be completed during 2007.
- Working with the FAA, NASA expanded the understanding of supersonic boom noise and our knowledge of how to reduce it. An initial study of the impact of atmospheric turbulence on very low noise sonic boom waveforms was also completed. NASA F-18 aircraft, flying a specially designed flight profile, were used to generate the booms. Indoor and outdoor waveform shapes, noise levels and building vibration data were recorded for use in model validation studies.

Hypersonics Project

- Pushed the "high end" of the flight envelope jointly with the Air Force, through the Mach 5 ground testing of a thermally-stable advanced hydrocarbon fueled scramjet. NASA teamed with the Air Force Research Laboratory and Pratt & Whitney Rocketdyne to complete the tests on the Ground Demonstration Engine - 2 in the NASA 8-Foot High Temperature Tunnel. The NASA tests marked the first time a hydrocarbon-fueled, fuel-cooled scramjet with full-authority digital engine control was tested at hypersonic conditions.
- The Preliminary Design Review for the Hypersonic Boundary Layer Transition Flight Experiment (Hy-BoLT) was completed. This NASA/ATK flight test will acquire data for the effects of protuberances and cavities on aerodynamic heating that will be of value to the Space Shuttle. The Hy-BoLT experiment will be launched atop the ATK ALV-X1 launch vehicle from the NASA Wallops Flight Facility in mid 2007.

Partnerships

(Some of these partnerships are still under discussion)

Fixed Wing Project

- **AFRL/Boeing/NASA Blended Wing Body.** Purpose: Flight and ground validation of low noise/improved performance aircraft configuration; system level integration & validation, acoustics, aerodynamics, controls & dynamics, materials & structures, experimental capabilities, physics-based multi-disciplinary analysis & optimization (PB-MDAO); flight research with X-48B.
- **Boeing / Quiet Technology Demonstrators 3 & 4.** Purpose: Flight testing of low noise / improved performance technologies; acoustics, aerodynamics, aerothermodynamics, combustion, controls and dynamics; future test bed for other discipline studies (e.g. alternative fuels).
- **P&W / NASA Ultra-High Bypass Engine Research.** Purpose: testing of Ultra-High Bypass Engine technology for low emissions, low noise, and improved performance; combustion, aerothermodynamics, materials & structures, controls & dynamics; wind tunnel tests; static engine and flight operability tests with P&W 747 test bed aircraft.

Rotary Wing Project

- **NASA/Center for Rotorcraft Innovation (CRI).** Purpose: On-going discussions of potential collaboration in a variety of rotorcraft-related areas including but not limited to 1) Joint NASA/Army/CRI/Bell Helicopter Flight Test for Acoustic Prediction Development and Low Noise Flight Profile Development, and 2) Active Rotor Control. CRI has requested an interaction with NASA to explore the possibilities of flight testing an active control rotor.
- **NASA/Helowerks, Inc.** Purpose: To provide technical expertise and computational modeling of a Helowerks landing gear system. Helowerks will provide test specimens and hardware to be used at the vertical drop facility.
- **NASA/Army/Sikorsky/ZFL.** Purpose: Full-Scale Individual Blade Control (IBC) Wind Tunnel Investigation.

Supersonics Project

- **NASA/Gulfstream Aerospace.** Purpose: Supersonic Inlet Concept Evaluation. Active Flow Control for Mechanically Simple Axisymmetric Supersonic Inlets. Series of tests planned to develop a mechanically simple, non-bleed, external compression inlet to operate up to Mach 2.
- **NASA/Lockheed Martin.** Purpose: Slender Aircraft Aeroelastics. Application of non-linear, high-fidelity analysis tools to the evaluation of the interaction of aeroelastic behavior with basic flight stability and control.
- **NASA/AFRL.** Purpose: Supersonic Tailless Control Effectors. Analytical study of innovative control devices for tailless supersonic aircraft configurations.

Hypersonics Project

- **NASA/ATK.** Purpose: Hypersonic Boundary Layer Transition Flight Experiment (Hy-BoLT). Natural transition data (upper surface) and Shuttle protuberance impact on transition (lower surface) will be measured. The upper surface flow physics experiment supports hypersonic code testing. The lower surface measurements are in support of testing of hypersonics engineering tools for shuttle Return-to-Flight.
- **NASA/Aerojet/AFRL.** Purpose: Aerojet 3D Inlet: Test of inlet in the Unitary Plan Supersonic Wind Tunnel and CFD analysis on Aerojet vehicle-integrated 3D inlet design.
- **NASA/AFRL/DARPA.** Purpose: The X-51A project. This project will flight test a hydrocarbon fueled, airframe-integrated 2D scramjet for five minutes. The vehicle will accelerate under scramjet power from Mach 4.5 to 6.5.

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AVIATION SAFETY PROGRAM

Through the vigilance of industry and government, the U.S. Air Transportation System is widely recognized as among the safest in the world. Looking at the projected increases in air traffic and future system capabilities, this vigilance must continue in order for the U.S. to meet both the public expectations for safety and the full realization of the Next Generation Air Transportation System (NGATS). To meet these challenges, the Aviation Safety Program will focus on developing cutting-edge technologies to improve the intrinsic safety attributes of current and future aircraft that will operate in the global NGATS. Furthermore, these technologies can be leveraged to support space exploration activities, in particular to enable the self-reliant and intelligent systems necessary for the long-duration travel requirements of future space vehicles. The Aviation Safety Program is comprised of the following four projects:

Integrated Vehicle Health Management (IVHM): This project will conduct research to advance the state of highly integrated and complex flight-critical health management technologies and systems. These technologies will enable nearly continuous on-board situational awareness of the vehicle health state for use by the flight crew, ground crew, and maintenance depot. Improved safety and reliability will be achieved by onboard systems capable of performing self-diagnostics and self-correcting of anomalies that could otherwise go unattended until a critical failure occurs.

Integrated Intelligent Flight Deck (IIFD): This project will pursue flight deck related technologies that ensure crew workload and situation awareness are both safely optimized and adapted to the future operational environment as envisioned by the NGATS. A key component of this research will be investigating methods to automatically monitor, measure, and assess the state of the crew awareness to their assigned task. Project results should enable system designers to eliminate the safety risk of unintended consequences when introducing new and advanced systems into an operational environment.

Integrated Resilient Aircraft Control (IRAC): This project will conduct research to advance the state of aircraft flight control automation and autonomy in order to prevent loss-of-control in flight. Taking into account the advanced automation and autonomy capabilities as envisioned by NGATS, the research will pursue methodologies to enable an aircraft to automatically detect, mitigate, and safely recover from an off-nominal condition that could lead to a loss of control.

Aircraft Aging and Durability (AAD): This project will develop advanced diagnostic and prognostic capabilities for detection and mitigation of aging-related hazards. The research and technologies to be pursued will decrease the susceptibility of current and next generation aircraft and onboard systems to pre-mature deterioration, thus greatly improving vehicle safety and mission success. The intent is to take a proactive approach to identifying aging-related hazards before they become critical, and to develop technology and processes to incorporate durability and aging mitigation into the design of future aircraft. Foundational research in aging science will ultimately yield Multidisciplinary Analysis and Optimization capabilities that will enable system-level integrated methods for detection, prediction, and mitigation/management of aging-related hazards for future civilian and military aircraft.

A Few of the Aviation Safety Program's Recent Accomplishments

Integrated Vehicle Health Management Project

The IVHM project has made key advances in sensor technologies, analytical tools, and construction of simulation and test-bed capabilities, to include improvements to the Icing Research Tunnel at the Glenn Research Center and the upgrade of a Viking S-3 aircraft. The S-3 swept wing design and greater performance envelope make this an important testbed for characterizing commercial transport environments (relevant for engine icing issues.) Structural anomaly detection methods were also developed and demonstrated using laboratory fatigue-cycle data from lap-splice panels instrumented with the NASA-developed Fiber Optic Strain System (FOSS).

Integrated Intelligent Flight Deck Project

The IIFD project made major advancements in data mining for information sharing, new crew-vehicle interfaces for managing workload and maintaining situational awareness, and assessments of forward looking sensor technologies for hazard detection. Activities include research in support of a joint government/industry Information Sharing Initiative (ISI) that developed tools for data archiving and retrieval. Recent research also includes an assessment of head-worn display media for safe and efficient surface operations in low-visibility conditions, and multiple studies addressing the optimal fusion of synthetic and enhanced vision system display concepts.

Integrated Resilient Aircraft Control Project

The IRAC project developed a new test capability for simulating upset flight conditions and a refined ability to characterize the in-flight effect of vehicle damage. The Airborne Subscale Transport Aircraft Research (AirSTAR) testbed was completed and will support research in upset modeling, and prevention and recovery of transport category aircraft. Preliminary structural damage computational models were also developed for a transport airframe under discrete source damage.

Aircraft Aging and Durability Project

The AAD project advanced methods for predicting crack growth and the use of advanced composites for engine fan blade failure containment. A multi-scale analysis methodology was developed to model damage processes. This work is critical to both developing better criteria for crack growth propagation and designing more damage tolerant and durable structural materials. Proof of concept demonstrations for an improved lightweight composite engine casing capable of fan blade failure containment was also completed through a synergistic partnership among small businesses, aircraft engine manufacturers, and universities.

Partnerships

(Some of these partnerships are still under discussion)

Current collaborative partnership efforts include:

- Development of high-temperature thin-film ceramic strain gauges to measure static strain characteristics of engine components at high temperatures (Air Force Research Lab [AFRL]).
- Development of meteorological instrumentation for automated landing capability (AFRL).
- Icing cloud instrumentation (NASA, Federal Aviation Administration [FAA], National Research Council, Canada, Meteorological Service of Canada [MSC]).
- Icing environment remote systems development (NASA, National Oceanic and Atmospheric Administration, FAA, Transport Canada, and MSC)

We also anticipate several new activities with industry that will be conducted under new Space Act Agreements. Potential partnerships include:

- General Electric Aircraft Engines for disk materials microstructural behavior and modeling; engine fan containment structure durability, and hot-section sensors and methods for measuring turbine temperatures.
- Williams International for superalloy disk durability and engine fan containment structure durability.
- Boeing Commercial Aircraft for progressive damage modeling of composites; durability of bonded joints; durability and damage tolerance of composite fuselage structures and damage containment in integrally-stiffened metallic structures.

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AIRSPACE SYSTEMS PROGRAM

The Airspace Systems Program (ASP) conducts cutting-edge research that will enable the Next Generation Air Transportation System (NGATS). In partnership with the Joint Planning and Development Office (JPDO), the ASP will help develop the concepts, capabilities and technologies that will lead to the significant enhancements in capacity, efficiency and flexibility needed to meet the Nation's airspace and airportal requirements for decades to come.

The Airspace Systems Program will focus on two major projects: NGATS Air Transportation Management (ATM) Airspace and NGATS ATM Airportal. Fundamental capabilities developed in one project will be leveraged for the benefit of the other to make efficient use of available resources. Outcomes from each project will be integrated for gate-to-gate solutions.

NGATS ATM-Airspace: This project will develop and explore fundamental concepts and integrated solutions that address the optimal use of ground and air automation technologies necessary for the NGATS. Research in this project will address Four-Dimensional Trajectory Operations including advances in the science and applications of multi-aircraft trajectory optimization that solves the demand/capacity imbalance problem and manages the separation assurance requirement. Researching Traffic Flow Management and Dynamic Airspace Configuration will enable more efficient use of airspace by addressing the technical challenges of migrating from the current structured, static homogenous airspace to a dynamic, heterogeneous airspace that adapts to changing constraints of users' preferences, weather, traffic congestion, and a highly diverse aircraft fleet. Ultimately, the roles and responsibilities of humans and automation touch every technical area and will be addressed thoroughly.

NGATS ATM-Airportal: This project will develop and validate algorithms, concepts, and technologies for use in enabling integrated solutions designed to safely increase capacity and efficiency in the airportal component of the air transportation system. Currently, the growth of air traffic demand and fleet diversity is causing the operational volume at hub airports to rapidly approach their maximum capacity. Research will develop solutions that safely integrate surface and terminal area air traffic optimization tools and systems with Four-D Trajectory Operations. These tools and systems will be aimed at mitigating the growing constraints at the nation's hubs (e.g., adverse weather and wake vortex hazards) to enable significant increases in airport throughput.

A Few of the Airspace System Program's Recent Accomplishments

The Future Air Traffic Management Concepts Evaluation Tool (FACET)

- FACET, a flexible software tool that models the National Airspace System, won NASA's Software of the Year for 2006 award. Its powerful simulation capabilities can rapidly generate thousands of aircraft trajectories to enable efficient planning of traffic flows at the national level.
- FACET has successfully transitioned from the NASA laboratory to national operational use.

The Virtual Airspace Modeling and Simulation (VAMS) Project

- Completed operational concept development. VAMS provides a detailed description of a future capacity enhancing concept for the National Airspace System and an assessment of its potential capacity benefits.
- The System-wide Concept assessment was performed using the VAMS-developed Airspace Concepts Evaluation System (ACES) assessment tool. ACES models gate-to-gate operations of the NAS. Using ACES, VAMS demonstrated that the VAMS System-wide Concept could accommodate the targeted 2X increase in capacity (relative to 1997 throughput).

Industry Outreach

- ASP conducted an Industry Outreach workshop June 14-15, 2006. Included among the participants were Boeing, Cessna, Honeywell, Lockheed Martin, Rockwell Collins and United Airlines.
- Objectives included sharing project material with potential industry partners; allowing industry representatives to share and expound on their RFI responses from January; and identifying appropriate areas of collaboration.

Partnerships

(Some of these partnerships are still under discussion)

Airspace System Program is working on several Space Act Agreements to include:

- Working with Lockheed Martin on Inter-operable Air Traffic Management (ATM) trajectories, and the Tactical Separation-Assisted Flight Environment (TSAFE) for the En Route Automation Modernization (ERAM) system.
- Working with Boeing to clarify requirements for the Tailored Arrival Research in Separation Assurance.
- Working with Raytheon for the use of ASTOR software in a Net/Centric JPDO Demonstration.
- Exploring how the UPS/FAA merging and spacing field evaluations can contribute to NASA data in Airspace Super Density. UPS/FAA needs help in researching the end state of heterogeneous highly automated airspace.

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AERONAUTICS TEST PROGRAM

To ensure that NASA sustains its strategically important aeronautics ground test capabilities, the agency has implemented the Aeronautics Test Program (ATP) under the Shared Capability Asset Program. The goals of the ATP are to:

- Provide corporate management of the aeronautical test facilities that are considered to be national assets
- Increase the probability of having the right facilities in place at the right time for future usage by NASA, the DOD, other government agencies, and the U.S aerospace industry and academic community
- Operate these facilities effectively and efficiently in order to maximize user value
- Ensure intelligent divestment of duplicative and/or unneeded capability while making sound and strategic investments in those facilities that NASA is committed to sustaining.

As a specific example of how ATP supports the agency and the nation, we note that the implementation of NASA's Vision for Space Exploration will require the development of the Crew Exploration Vehicle, the Crew Launch Vehicle, and the Cargo Launch Vehicle. These development projects will require many hours of wind tunnel testing in the future across the speed range from subsonic to hypersonic. The ATP will ensure availability of the required wind tunnel testing capabilities to support the timely development of these vehicles without unduly burdening the Exploration Systems program with sustaining these test facilities in the interim.

The ATP has been structured to provide strategic management of the aeronautics ground test facilities at NASA's Ames, Glenn and Langley Research Centers. The four major elements of the ATP are:

- Operations support that provides funding for 60-75 percent of the fixed costs of a critical set of wind tunnels and air breathing propulsion test facilities to establish stable pricing commensurate with comparable domestic and foreign test facilities

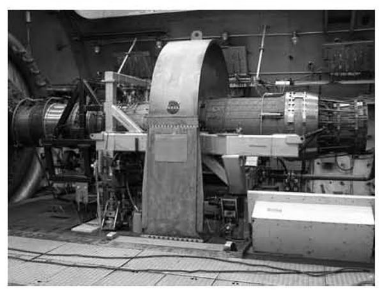
- Investments to support major non-routine maintenance projects to ensure long-term facility health
- Investments to support both the development and implementation of new test technologies; and
- Support for research in aeronautical facilities at the university level to train future researchers in the area of experimental fluid mechanics and aerodynamics.

Aeronautics Test Program's Recent Accomplishments

By implementing the ATP, NASA is sustaining the suite of ground testing capabilities that are critical to the Nation's future aeronautics testing needs. This is the ATP's principle accomplishment. Previously, the NASA Research Centers had the sole responsibility for the operations and maintenance of wind tunnels and air-breathing engine test cells without management oversight or direct financial assistance from NASA Headquarters. With decreasing use of ground test facilities came the inability of the Centers to sustain these valuable national assets. A notable example was the closure of the National Full-Scale Aerodynamics Complex by the NASA Ames Research Center. This event served as an alarm that prompt action was needed to ensure that additional unique facilities did not meet a similar fate.

Other specific accomplishments of the ATP in FY06 include exceeding the projected utilization of ATP ground test facilities, reducing the backlog of overdue maintenance activities in the ATP facilities, initiating test technology investments including standardizing wind tunnel measurement systems across all NASA Research Centers and developing test facility control system simulators, which allow facility engineers to simulate test operations for purposes of facility check-out and operator training.

Partnerships



A new National Partnership for Aeronautics Testing (NPAT) is being developed between NASA and the Department of Defense (DoD) to provide a national approach to test facility management. Plans call for engaging the aerospace industry as a partner in NPAT. The ATP management structure enables NASA to work effectively with DoD and industry to implement this partnership. The recently released National Research Council's Decadal Survey of Civil Aeronautics calls on NASA to "maintain state-of-the art testing capabilities" in order for NASA to be a leader in cutting-edge aeronautics research. This recommendation aligns well with ATP goals and objectives and further strengthens the case for having in place the strong and centralized corporate management provided via the ATP.

BIOGRAPHY FOR LISA J. PORTER

Lisa J. Porter, the Associate Administrator for the Aeronautics Research Mission Directorate, leads the Agency's aeronautics research efforts and is co-lead in the development of a national aeronautics policy in cooperation with other government agencies. She most recently served as the NASA Administrator's senior adviser for aeronautics.

Porter came to the agency following her service as senior scientist in the Advanced Technology Office of the Defense Advanced Research Projects Agency in Arlington, Va. While there, she created and managed programs in diverse technical areas ranging from fundamental scientific research to multi-disciplinary systems-level development and integration efforts. Two of her programs focused on developing physics-based predictive design tools that leveraged advanced computational fluid dynamics.

The Helicopter Quieting Program, focused on developing the capability to design quiet rotor blades with minimal impact on aircraft performance. The Friction Drag Reduction Program focused on developing the capability to implement friction drag reduction technologies on naval platforms.

Porter has a Bachelor's degree in nuclear engineering from the Massachusetts Institute of Technology, Cambridge, Mass., and a doctorate in applied physics from Stanford University, Calif. She was a lecturer and postdoctoral research associate at MIT. She received the Alpha Nu Sigma MIT Student Chapter Outstanding Teaching Award in 1996. She has authored more than 25 publications in a broad range of technical disciplines including nuclear engineering, solar physics, plasma physics, computational materials modeling, explosives detection and vibration control of flexible structures.

Chairman CALVERT. Thank you for your testimony, Doctor.

Now, we are pleased to recognize Major General Hoover. You are recognized, sir. General, please, if you could speak directly into the mic it would be helpful. Thank you. There is a green button there to push. There we go.

STATEMENT OF MAJ. GEN. WILLIAM HOOVER (RET.), CO-CHAIR, NATIONAL ACADEMY OF SCIENCES' STEERING COMMITTEE

Major General HOOVER. Thank you. I apologize.

Thank you, Mr. Chairman, for the opportunity to testify before you today. My name is William Hoover. I am a former Executive Vice President of the Air Transport Association of America, a retired Major General from the United States Air Force, and former Chairman of the National Aeronautics and Space Engineering Board. I would request that my formal remarks be—formal statement be submitted for the record.

Chairman CALVERT. Without objection, so ordered, sir.

Major General HOOVER. It has been a while since Dr. Kaminski testified before you on July 18. He was the Chairman of the Decadal Survey. I would like to summarize in my remarks some of the points he has made, and add a few of my own.

As he indicated, the study was organized with a steering committee of 15 members. We had five panels across varying disciplines, aeronautical disciplines, which included another 50 panel members, and we had presentations from a number of other outside experts.

Because there was not a national aeronautics policy, we felt it incumbent the steering committee to establish some guidelines upon which the panels would have a basis for determining their research and technology challenges. We selected six strategic objectives. Capacity, safety, and reliability were our highest priorities. Efficiency and performance, energy, and environment were of next importance. Because we concentrated on civil aeronautics, the synergies with national and homeland security and support for space were of lesser priority in the work of our committee.

The other pillar of our guidance had to do with why NASA? We believed that since we were doing this study for NASA, we had to really determine where the research was appropriate for NASA. We identified four factors: supporting infrastructure, mission alignment, lack of alternative sponsors, and appropriate level of risk.

We use a methodology. It looks a little complicated. Dr. Kaminski tried to explain it in his previous testimony. I just want to leave you with the thought that this is a flexible process to make decisions on complex issues, bringing qualitative judgings together of a large number of experts. In quantitative terms, what it does for you, it gives you results that are traceable, they can be replicated, and they can be adjusted if a different set of priorities comes in the future, such as—it might be the outcoming of a national aeronautics policy.

The next chart I have modified somewhat. It might be the one appearing before you, but I thought it was useful to discuss why we felt there were other factors, other than the research and technology challenges that were important to comment on in our study. Basically, we identified a number of areas that dealt with transitioning technology to the public use. We felt that is the bottom line—the importance of the research and technology funding.

We talked about barriers. Barriers basically involve other agencies. We identified two.

Certification. As systems become more complex, it becomes more difficult to validate certification for safe entry in the air transportation system, particularly with the burgeoning software developments that have come along. NASA, we believe, needs to take the issue of certification into consideration further up in its research, and perhaps even conduct some research related to certification.

The second is change management, and this we relate to bringing new technology and systems into a broader context of interactive systems, such as our air traffic control system. This is a system that is very complex. It has not only got organizational issues, research and technology issues, operational issues. So it is very difficult when you bring new technology or a new system into this environment, and we think that the change management is an issue that needs to be addressed.

There are additional factors. Dr. Porter has already mentioned technology readiness reviews. I think there is some commonality in our thinking. We agree that there isn't one level that seems appropriate to work for all cases. In fact, in our report we said and explained why we believe one size doesn't fit all and we gave our rationale for whatever it is called, technology readiness levels or whenever the transition of technology of whatever kind makes sense in different circumstances.

We also had somewhat of a contentious issue with regard to the allocation of resources between in-house and external organizations. We were informed in January of this year that the split would be 93 percent and seven percent. Over the intervening months, we were told that this number was in flux, but we never really did get a firm number. Dr. Porter has just explained further rationale; however, in looking at her statement, I see—still see that $50 million of that $180 million that she talked about is going to external. The rest is going, basically, to support contractors for internal NASA work. I still do not see that this is, in fact, funding that is going out to industry, in particular where we see it may be important in hopes of facilitating transfer. We didn't comment on what the split should be. We think it is skewed too far. If it is perhaps anything above 70/30, but again, I think it remains an issue for the Congress to consider further.

Turning to our recommendations, I am only going to pick a few of them. Recommendation one is that NASA should use the 51 highest priority research and technology challenges that we identified as a foundation for their future program. At this time, it is difficult for us to determine the commonality in the program that Dr. Porter has laid out. I think this will take some time, but I think what we have done is given you at least a basis for contrast. Our recommendations, as I said, have a methodology that you can follow through in tracing how we came to our recommendations. It is based on an independent outside review. At the end of a day, the NASA program, even though they had many sessions where they listened to industry and outside sources, at the end of the day, it is a program that has been developed by NASA in-house. So at least you have a basis for contrast and comparison. Maybe they will be very closely aligned.

Other recommendations, recommendation three, I was very pleased to see in Dr. Porter's statement that we have a great deal of agreement on the five common themes that we identified in our report, and I think they are as important as they are applicable across several of the research and technology challenges. I think these facilitate the system of systems evolution and encourage a synergy for NASA funding.

Recommendation five addresses the change management issue. Today, the way we bring systems in to the complex interactive systems that we have, such as air traffic control system, is through coordination, cross fertilization, and frankly, it has resulted in some fractured approaches in the past. My personal view is there is a need for a more homogenous organizational approach. I think the Joint Development and Planning Office was an ad hoc approach to this problem. I think it needs to be considered in further context to other aeronautical issues.

Recommendation eight somewhat is set up by that previous recommendation. We believe it is time that the government should conduct a high level review of organizational options for ensuring U.S. leadership in civil aeronautics. This is broader than NASA to undertake, and in fact, NASA may resist this, but we believe the time has come. The Aldridge Commission, the President's Commission on Aerospace, while they didn't make specific recommendations, did discuss this issue and said at sometime it needed to be looked at. It will require either the Administration or Congress perhaps to step up and to bring this about. Perhaps the Congress will have to do this.

Dr. Kaminski made a few points on what sets our study apart from other studies in the past. I am not going to go through the full list again. I do feel that it is important that it be recognized that the Department of Defense has a very sophisticated requirements process, a very strong push/pull between the war fighters and the research and technology community. Dr. Porter's statement clarifies that NASA doesn't have that same user dynamic relationship, and therefore, it has been difficult over the years for NASA to go to the OMB and the Congress and say that we believe that these are requirements that underlie our research requests—funding requests. We believe that our study will help NASA in that regard.

We do believe we have given you a methodology that you can use for a variety of ways to look at how our program is developed, and to compare future programs. We have identified what we believe are some barriers and other factors that need to be addressed that are beyond research and technology challenges, per se. We have identified multi-agency issues that we believe call for organizational looks, and I think we have established, in the course of doing our study, that there is a need for a national aeronautics policy.

I would now like to say—just get off the stage by saying I have some personal concerns about where civil aeronautics is going. A national policy, I think we need it. It needs to be tied to national goals, such as where we are trying to go with world leadership in aeronautics, the competitive issues. It is not just something that can be used to define research and technology for research and technology.

Transition of technology, I think this is important. Fundamental research is important. I agree that what Dr. Porter is trying to do will make some important contributions. I guess sort of falling back on my military days, but I guess to a point where at some time it is time to go out and kill something, and I think you need to think about getting this into the systems, into the operational systems, into something that the public is actually going to be able to use. I think there is some urgency for solutions. I don't think the next generation air traffic control system can wait for necessarily the fundamental research to come along. It is not the next next generation system, it is the next system that we need to get on board. I think the issue of looking at the organizational options can't wait for another Administration to come on board. I think there are questions about synergy with space and defense, and finally, about the priorities within NASA.

Thank you very much, sir.

[The prepared statement of Major General Hoover follows:]

PREPARED STATEMENT OF MAJOR GENERAL WILLIAM HOOVER

Good afternoon, Mr. Chairman, and Members of the Committee. Thank you for the opportunity to testify before you today. My name is William Hoover. I am the former Executive Vice President of the Air Transport Association, and retired from the United States Air Force as a major general. I appear before you today in my capacity as co-chair of the National Research Council's Committee on the Decadal Survey of Civil Aeronautics.

The National Research Council is the operating arm of the National Academy of Sciences, National Academy of Engineering, and the Institute of Medicine of the National Academies, chartered by Congress in 1863 to advise the government on matters of science and technology.

In 2005, NASA requested that the National Research Council (NRC) establish the Committee on the Decadal Survey of Civil Aeronautics under the auspices of the Aeronautics and Space Engineering Board. The committee was charged with developing an overarching roadmap for investment in aeronautics research and technology at NASA, and assessing how federal agencies can more effectively address key issues and challenges. Our committee's report was released in June of 2006.

The U.S. air transportation system is a key contributor to the economic vitality, public well-being, and national security of the United States. The next decade of U.S. civil aeronautics research and technology (R&T) development should provide a foundation for achieving four high-priority Strategic Objectives:

- Increase capacity.
- Improve safety and reliability.
- Increase efficiency and performance.
- Reduce energy consumption and environmental impact.

Civil aeronautics R&T should also consider two lower-priority Strategic Objectives:

- Take advantage of synergies with national and homeland security.
- Support the space program.

The purpose of the Decadal Survey of Civil Aeronautics was to develop a foundation for the future—a decadal strategy for the Federal Government's involvement in civil aeronautics, with a particular emphasis on the National Aeronautics and Space Administration's (NASA's) research portfolio. A quality function deployment (QFD) process was used to identify and rank 89 R&T Challenges in relation to their potential to achieve the six Strategic Objectives listed above.[1] That process produced a list of 51 high-priority R&T Challenges that must be overcome to further the state of the art (see Table 1). These high-priority Challenges are equally divided among five R&T Areas:

- Area A: Aerodynamics and aeroacoustics.
- Area B: Propulsion and power.
- Area C: Materials and structures.
- Area D: Dynamics, navigation, and control, and avionics.
- Area E: Intelligent and autonomous systems, operations and decision making, human integrated. systems, and networking and communications.

Advances in these Areas would have a significant, long-term impact on civil aeronautics. Accordingly, federal funds, facilities, and staff should be made available to advance the high-priority R&T Challenges in each Area.

Five Common Themes summarize threads of commonality among the 51 high-priority R&T Challenges:

- Physics-based analysis tools to enable analytical capabilities that go far beyond existing modeling and simulation capabilities and reduce the use of empirical approaches.
- Multi-disciplinary design tools to integrate high-fidelity analyses with efficient design methods and to accommodate uncertainty, multiple objectives, and large-scale systems.
- Advanced configurations to go beyond the ability of conventional technologies and aircraft to achieve the Strategic Objectives.
- Intelligent and adaptive systems to significantly improve the performance and robustness of aircraft and the air transportation system as a whole.
- Complex interactive systems to better understand the nature of and options for improving the performance of the air transportation system, which is itself a complex interactive system.

These Themes are not an end in themselves; they are a means to an end. Each Theme describes enabling approaches that will contribute to overcoming multiple Challenges in the five R&T Areas. Exploiting the synergies identified in each Common Theme will enable NASA's aeronautics programs to make the most efficient use of available resources.

Even if individual R&T Challenges are successfully overcome, two key barriers must also be addressed before the Strategic Objectives can be accomplished:

- *Certification.* As systems become more complex, methods to ensure that new technologies can be readily applied to certified systems become more difficult to validate. NASA, in cooperation with the FAA, should anticipate the need to certify new technology before its introduction, and it should conduct re-

[1] QFD is a group decision-making methodology often used in product design.

search on methods to improve both confidence in and the timeliness of certification.

- *Management of change, internal and external.* Changing a complex interactive system such as the air transportation system is becoming more difficult as interactions among the various elements become more complex and the number of internal and external constraints grows. To effectively exploit R&T to achieve the Strategic Objectives, new tools and techniques are required to anticipate and introduce change.

The report also encourages NASA to do the following:

- Create a more balanced split in the allocation of aeronautics R&T funding between in-house research (performed by NASA engineers and technical specialists) and external research (by industry and/or universities). As of January 2006, NASA seemed intent on allocating 93 percent of NASA's aeronautics research funding for in-house use.
- Closely coordinate and cooperate with other public and private organizations to take advantage of advances in cross-cutting technology funded by federal agencies and private industry.
- Develop each new technology to a level of readiness that is appropriate for that technology, given that industry's interest in continuing the development of new technologies varies depending on urgency and expected payoff.
- Invest in research associated with improved ground and flight test facilities and diagnostics, in coordination with the Department of Defense and industry.

The eight recommendations formulated by the steering committee summarize action necessary to properly prioritize civil aeronautics R&T and achieve the relevant Strategic Objectives:

Recommendation 1. NASA should use the 51 Challenges listed in Table 1 as the foundation for the future of NASA's civil aeronautics research program during the next decade.

Recommendation 2. The U.S. Government should place a high priority on establishing a stable aeronautics R&T plan, with the expectation that the plan will receive sustained funding for a decade or more, as necessary, for activities that are demonstrating satisfactory progress.

Recommendation 3. NASA should use five Common Themes to make the most efficient use of civil aeronautics R&T resources:

- Physics-based analysis tools
- Multi-disciplinary design tools
- Advanced configurations
- Intelligent and adaptive systems
- Complex interactive systems

Recommendation 4. NASA should support fundamental research to create the foundations for practical certification standards for new technologies.

Recommendation 5. The U.S. Government should align organizational responsibilities as well as develop and implement techniques to improve change management for federal agencies and to assure a safe and cost-effective transition to the air transportation system of the future.

Recommendation 6. NASA should ensure that its civil aeronautics R&T plan features the substantive involvement of universities and industry, including a more balanced allocation of funding between in-house and external organizations than currently exists.

Recommendation 7. NASA should consult with non-NASA researchers to identify the most effective facilities and tools applicable to key aeronautics R&T projects and should facilitate collaborative research to ensure that each project has access to the most appropriate research capabilities, including test facilities; computational models and facilities; and intellectual capital, available from NASA, the Federal Aviation Administration, the Department of Defense, and other interested research organizations in government, industry, and academia.

Recommendation 8. The U.S. Government should conduct a high-level review of organizational options for ensuring U.S. leadership in civil aeronautics.

This report should provide a useful foundation for the ongoing effort in the executive branch to develop an aeronautics policy. In addition, even though the scope of this study purposely did not include specific budget recommendations, it should support efforts by Congress to authorize and appropriate the NASA aeronautics budget.

Thank you for the opportunity to testify. I would be happy to take any questions the Committee might have.

COMMITTEE ON DECADAL SURVEY OF CIVIL AERONAUTICS

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TABLE 1 Fifty-one Highest Priority Research and Technology Challenges for NASA Aeronautics, Prioritized by R&T Area

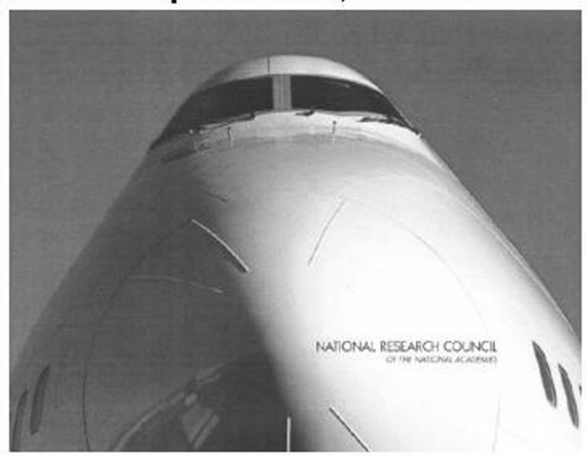
A Aerodynamics and Aeroacoustics	B Propulsion and Power	C Materials and Structures	D Dynamics, Navigation, and Control, and Avionics	E Intelligent and Autonomous Systems, Operations and Decision Making, Human Integrated Systems, Networking and Communications
A1 Integrated system performance through novel propulsion-airframe integration	B1a Quiet propulsion systems	C1 Integrated vehicle health management	D1 Advanced guidance systems	E1 Methodologies, tools, and simulation and modeling capabilities to design and evaluate complex interactive systems
A2 Aerodynamic performance improvement through transition, boundary layer, and separation control	B1b Ultraclean gas turbine combustors to reduce gaseous and particulate emissions in all flight segments	C2 Adaptive materials and morphing structures	D2 Distributed decision making, decision making under uncertainty, and flight path planning and prediction	E2 New concepts and methods of separating, spacing, and sequencing aircraft
A3 Novel aerodynamic configurations that enable high performance and/or flexible multi-mission aircraft	B3 Intelligent engines and mechanical power systems capable of self-diagnosis and reconfiguration between shop visits	C3 Multidisciplinary analysis, design, and optimization	D3 Aerodynamics and vehicle dynamics via closed-loop flow control	E3 Appropriate roles of humans and automated systems for separation assurance, including the feasibility and merits of highly automated separation assurance systems
A4a Aerodynamic designs and flow control schemes to reduce aircraft and rotor noise	B4 Improved propulsion system fuel economy	C4 Next-generation polymers and composites	D4 Intelligent and adaptive flight control techniques	E4 Affordable new sensors, system technologies, and procedures to improve the prediction and measurement of wake turbulence
A4b Accuracy of prediction of aerodynamic performance of complex 3D configurations, including improved boundary layer transition and turbulence models and associated design tools	B5 Propulsion systems for short takeoff and vertical lift	C5 Noise prediction and suppression	D5 Fault tolerant and integrated vehicle health management systems	E5 Interfaces that ensure effective information sharing and coordination among ground-based and airborne human and machine agents
A6 Aerodynamics robust to atmospheric disturbances and adverse weather conditions, including icing	B6a Variable-cycle engines to expand the operating envelope	C6a Innovative high-temperature metals and environmental coatings	D6 Improved onboard weather systems and tools	E6 Vulnerability analysis as an integral element in the architecture design and simulations of the air transportation system
A7a Aerodynamic configurations to leverage advantages of formation flying	B6b Integrated power and thermal management systems	C6b Innovative load suppression, and vibration and aeromechanical stability control	D7 Advanced communication, navigation, and surveillance technology	E7 Adaptive ATM techniques to minimize the impact of weather by taking better advantage of improved probabilistic forecasts
A7b Accuracy of wake vortex prediction, and vortex detection and mitigation techniques	B8 Propulsion systems for supersonic flight	C8 Structural innovations for high-speed rotorcraft	D8 Human-machine integration	E8a Transparent and collaborative decision support systems
A9 Aerodynamic performance for V/STOL and ESTOL, including adequate control power	B9 High-reliability, high-performance, and high-power-density aircraft electric power systems	C9 High-temperature ceramics and coatings	D9 Synthetic and enhanced vision systems	E8b Using operational and maintenance data to assess leading indicators of safety
A10 Techniques for reducing/mitigating sonic boom through novel aircraft shaping	B10 Combined-cycle hypersonic propulsion systems with mode transition	C10 Multifunctional materials	D10 Safe operation of unmanned air vehicles in the national airspace	E8c Interfaces and procedures that support human operators in effective task and attention management
A11 Robust and efficient multidisciplinary design tools				

Decadal Survey of Civil Aeronautics

FOUNDATION FOR THE FUTURE

William Hoover, Co-Chair

September 26, 2006



National Research Council

Aeronautics and Space Engineering Board

Strategic Objectives

- Capacity
- Safety and reliability
- Efficiency and performance
- Energy and the environment
- Synergies with national and homeland security
- Support to space

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Why NASA?

- Supporting infrastructure
- Mission alignment
- Lack of alternative sponsors
- Appropriate level of risk

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Qualitative Judgments – Quantitative Basis

R&T Challenge	Strategic Objective						National Priority	Why NASA?					NASA Priority Score
	Capacity	Safety and Reliability	Efficiency and Performance	Energy and the Environment	Synergies with Security	Support to Space		Supporting Infrastructure	Mission Alignment	Lack of Alternative Sponsors	Appropriate Level of Risk	Why NASA Composite Score	
Weight	5		3		1			$^1/_4$ each					
X1 R&T Challenge 1	9	9	3	3	1	1	**110**	3	9	3	9	**6.0**	**660**
X2 R&T Challenge 2	3	9	3	9	1	1	**98**	1	9	3	9	**5.5**	**539**
X3 R&T Challenge 3	1	1	1	3	9	9	**40**	9	9	9	9	**9.0**	**360**

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Technology Areas

- Aerodynamics and aeroacoustics
- Propulsion and power
- Materials and structures
- Dynamics, navigation, and control, and avionics
- Intelligent and autonomous systems, operations and decision making, human integrated systems, and networking and communications

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Barriers

- Certification
- Change management

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Civil Aeronautics Quo Vadis?

- National policy
- Synergy with space and defense
- Priority within NASA
- Urgency of solutions

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What Sets This Study Apart?: Some Thoughts from the Co-Chair

- Serves as a de facto requirements document for civil aeronautics R&T
- Demonstrates a target rich environment exists for aeronautics R&T
  - Counters the mature technology argument
- Prioritizes R&T using quantitative basis with the flexibility to adjust to future considerations
- Addresses why NASA should undertake specific R&T
- Identifies opportunities for synergistic R&T (research thrusts and common themes)
- Shows that one size fits all not appropriate when setting TRL goals for NASA aeronautics research

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What Sets This Study Apart?: Some Thoughts from the Co-Chair

- Emphasizes importance of systems of systems analysis and systems integration factors in determining R&T requirements and programs
- Identifies barriers that hamper transfer of R&T results to operational systems
- Shows that a heavily skewed budgetary allocation (that minimizes participation of academia and industry) impedes
  - the timely transfer of R&T results to industry
  - the growth of new talent in academia
- Identifies multi-agency issues and calls for a study of organizational options to facilitate U.S. leadership in civil aeronautics
- Shows the importance of establishing a national aeronautics policy by demonstrating the impact of strategic objectives on R&T goals and requirements

Recommendation 1

NASA should use the 51 highest priority R&T Challenges as the foundation for the future of NASA's civil aeronautics research program during the next decade.

Recommendation 2

The U.S. government should place a high priority on establishing a *stable* aeronautics R&T plan, with the expectation that the plan will receive sustained funding for a decade or more, as necessary, for activities that are demonstrating satisfactory progress.

Recommendation 3

NASA should use five Common Themes to make the most efficient use of civil aeronautics R&T resources:

- **Physics-based analysis tools**
- **Multidisciplinary design tools**
- **Advanced configurations**
- **Intelligent and adaptive systems**
- **Complex interactive systems**

Recommendation 4

NASA should support fundamental research to create the foundations for practical certification standards for new technologies.

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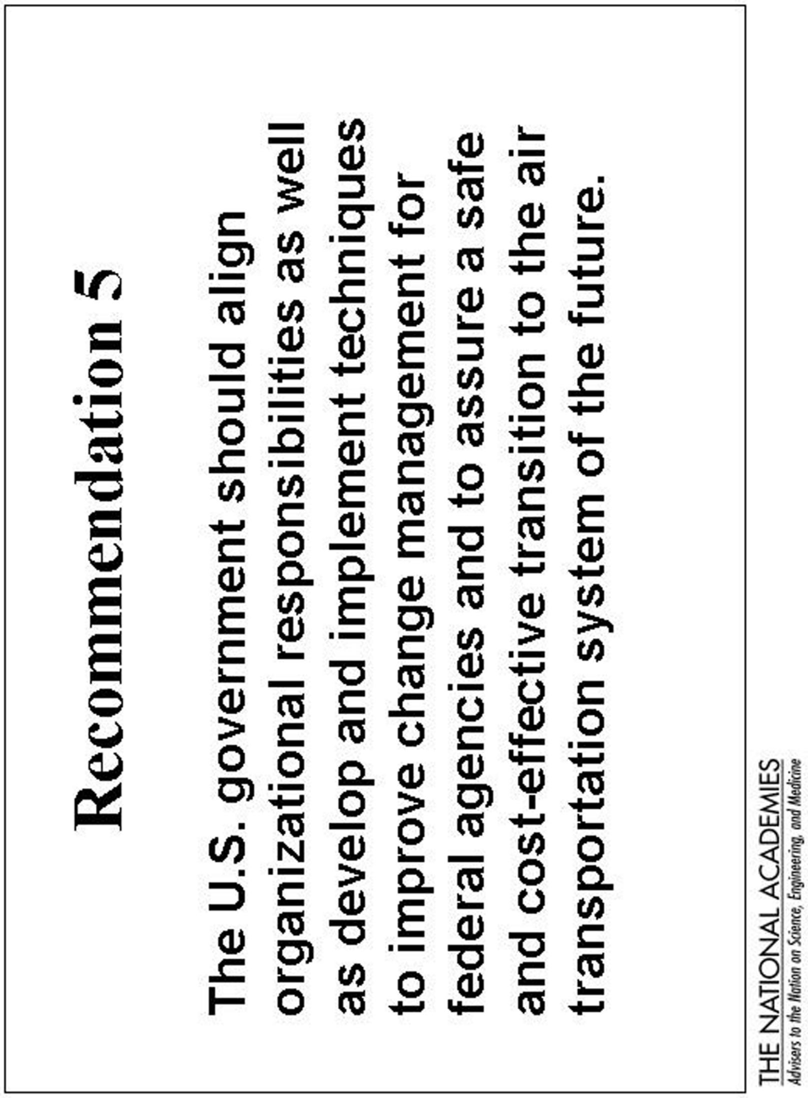
Recommendation 5
The U.S. government should align organizational responsibilities as well as develop and implement techniques to improve change management for federal agencies and to assure a safe and cost-effective transition to the air transportation system of the future.
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Recommendation 6

NASA should ensure that its civil aeronautics R&T plan features the substantive involvement of universities and industry, including a more balanced allocation of funding between in-house and external organizations than currently exists.

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Recommendation 7

NASA should consult with non-NASA researchers to identify the most effective facilities and tools applicable to key aeron. R&T projects and facilitate collaborative research to ensure that each project has access to the most appropriate research capabilities, incl. test facilities; computational models and facilities; and intellectual capital, available from NASA, FAA, DoD, and other interested research organizations in gov't, industry, and academia.

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Recommendation 8

The U.S. government should conduct a high-level review of organizational options for ensuring U.S. leadership in civil aeronautics.

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Discussion

NASA's Response to the Decadal Survey Recommendations

Chairman CALVERT. Thank you for your testimony, General.

Doctor, of the Decadal Survey recommendations and high priority challenges, are there any of those of which you take exception to?

Dr. PORTER. Let me just pull up my sheet on this so I answer your question correctly.

We actually did a cross cut matrix of all the 51 technical challenges that were recommended, and we looked at our own roadmaps to identify where—if they did exist in our programs, where they laid out. We found that 47 of the 51, so that is greater than 90 percent of those recommendations are presently being addressed in our current research portfolio.

Chairman CALVERT. Were there, in your opinion while you are on that, were there omissions that should have been included also?

Dr. PORTER. There are other things that we are addressing that were on their list but at a lower level. In particular, as General Hoover mentioned, they did not put as high an emphasis on applications to our partners in the DOD, nor to our partners in the space side. And so some of the hypersonics challenges received a lower rating than we actually had in our own portfolio. But for the most part, we think that the recommendations that they had present a good breadth of capability and we think that we have got a very good cross correlation with those recommendations.

Hypersonic Funding

Chairman CALVERT. While we are on the issue of hypersonics, in your '07 budget request hypersonics research received the second highest allocation of funding. I believe it was about $114 million, among all proposed projects for civil aeronautics research. And so obviously, that is a significant priority, and as proposed, it is slated to get more funding than the supersonic R&D budget, which is, I believe, about $85 million; the Aviation Safety budget which is $102 million; and almost the same funding for the entire airspace systems R&D, which is about $120 million.

So I guess the question would be what is NASA's rationale? Is hypersonics that high a priority for the civil industry, or is there some other issue going on that we are not aware of?

Dr. PORTER. The way we structured out our portfolio is to ensure that we align with the core principles we established, and one of those core principles is to ensure mastery across all of the flight regimes in the core competencies of aeronautics. We must pursue the frontiers of flight. That is what we do for the Nation and that frontier does not stop at Mach 1, obviously. We need to be very vigilant in ensuring that we are always on the cutting edge in hypersonics, supersonics, subsonics. In all that continual spectrum of flight regimes, we have to ensure that we are on the cutting edge. Hypersonics is part of that cutting edge.

I will tell you that during the NRA, we received, as you know, 700 proposals. Over 100 proposals came in from universities in hypersonics. When you talked to students out there as I have done, hypersonics represents the unknown. It represents what we do not yet understand or master, and therefore, it is a very exciting area of research. I would also point out that that fact is well-recognized around the world, so I feel that NASA has a very important commitment there.

Chairman CALVERT. General Hoover, what are your views about the level of hypersonics?

Major General HOOVER. Well, as I said, we focused on—since NASA is the only really research and technology agency devoted to civil aeronautics, we tried to focus our view on how the NASA budget—aeronautics budget could best be used to that end.

I don't disagree with Dr. Porter that hypersonics is an important research area. I would perhaps suggest that if it is that important, maybe she should be getting some help in her funding from other people's budgets.

Chairman CALVERT. Well, on that subject, Doctor, are there others involved in hypersonics with you? DARPA, DOD?

Dr. PORTER. Yes, absolutely. The X–51 program which NASA is a part of is also being funded by DARPA and the Air Force. In fact, DARPA and the Air Force are contributing most of the procurement dollars to that. NASA is bringing to bear its own in-house expertise, as well as partnership outreach opportunities with the universities as I just explained. Not to mention, our unique world class facilities, most notably our eight foot tunnel at Langley where we just recently, as I mentioned, completed some cutting edge firsts of their kind hypersonics tests with the Air Force.

Chairman CALVERT. I will come back for some more questions.

Mr. Udall, you are recognized.

Mr. UDALL. Thank you, Mr. Chairman.

FUTURE OF AERONAUTICS RESEARCH

If I might, I will start with Dr. Porter. You have undoubtedly heard the concerns expressed by many in the aeronautics community about the decline in the NASA budget. You and I have had spirited discussions of this situation. As well, I want to thank you for your service.

Do you consider yourself to be an advocate for additional aeronautics funding within NASA, and if so, why, and if not, why not?

Dr. PORTER. Sir, I am not sure I understood the question. Do I consider myself an advocate for——

Mr. UDALL. For additional aeronautics funding within NASA.

Dr. PORTER. I consider myself an advocate for a strong aeronautics program, and I believe that is what we have.

Mr. UDALL. If I could turn to the General. Where do you think the long-term prognosis for the research program and for the health of the aeronautics in the U.S. is if current budgetary trends continue, General?

Major General HOOVER. Well, I think I would share Dr. Kaminski's view that there is a concern that the trend is not conducive to supporting a strong aeronautics research program, and that if it continues in this downward trend—we are already, I think, at a marginal level for funding, and we are getting to a point whether it is really going to be possible to really continue something that really will be relevant.

Mr. UDALL. What I hear you saying is we still have airspeed today, but we will stall at some point?

Major General HOOVER. That would be a good aeronautical analogy.

TECHNOLOGY READINESS LEVELS

Mr. UDALL. And once you stall, you fall like a rock.

If I could turn to a more specific area, although on the heels of the previous question. In Dr. Porter's testimony, she stated that one can develop a device to a high technology readiness level, but that in no way guarantees that it will successfully transition into industry. That statement, to me, seems to confirm the point that the Decadal Survey and other groups have been making, namely that without the active involvement of industry in NASA's aeronautics program, that the research NASA does runs the risk of being not relevant or applicable to societal or government needs.

If I looked at the TRLs, the Technology Readiness Levels, why do the Decadal Survey participants believe that is important for NASA to carry some research to higher levels of maturity than others, and not to confine all of NASA's research to just basic research?

Major General HOOVER. Well, there is the concern, I think, about—again, in Dr. Porter's statement about funding something that would be useful, perhaps, for just one corporation. I realize that is a concern, but when technology is at a point where in today's environment, industry cannot make the business case to bringing the bottom line back to its stockholders—an improvement to the bottom line. Within two or three years, they are not anxious to pursue that technology in-house. They, I think—and justifiably, should be interested in NASA funding the longer-term research, and in that case, until the research has gotten to a point where industry feels comfortable that, in fact, they can bring it on board and continue to develop it themselves, I think in those instances then NASA has to take that technology research level further down the road. Where industry is very interested in something that they can see quick return, and ask to turn it over to them, perhaps at a TRL level two or three.

The same kinds of considerations go when they talk about turning it over to other government agencies. If they are turning it over to the Department of Defense, which has a strong research and technology basis in their laboratories and Centers, again, they could turn that research over at a much lower technology research level because the Department of Defense can then pick it up on their own and continue it. When you turn it over to an agency like the FAA, that might be a different situation. In that case, it might be necessary first to get that technology into industry, and again, that would be at a point where industry felt that in turn they could provide it to the FAA and make some kind of, you know, some kind of profit.

So again, the technology research level would be at a different point, so I think we sort of agree, certainly, TRL level six is not, you know, the one-size-fits-all approach.

Mr. UDALL. My time is about to expire, and I do want to give other members a chance. I think we will get a second round of questions.

But what I hear you saying, and I have to confess, and I have confessed to Dr. Porter and confess to you—everybody is here, I am the consummate layperson. I am not a scientist. I am not a technologist, but I know how important this is to our future.

But I hear you saying that, at some level, your concern is that we are putting a one size fits all strategy in place, and that in fact, you need a lot of flexibility to meet—so that industry and NASA team up, and that the technologies that are emerging can vary in the support they need at one point or another along the spectrum.

Major General HOOVER. Well, I would agree with that, and I don't know that there is a conscious effort to put a strategy in place, but I think some in the past have thought well, gee, there must be some level that that all works at, and that is not the case.

Mr. UDALL. Thank you.

NASA AND CHINA

Chairman CALVERT. Mr. Forbes, you are recognized for five minutes.

Mr. FORBES. Thank you, Mr. Chairman. Mr. Chairman, thank you for holding this hearing, and Dr. Porter and General Hoover, thank you for the work you do, for being here today, and also, for your written statements.

And Dr. Porter, I just have a question for you. It is my understanding that NASA Administrator Griffin is in China this week visiting his counterpart at the China National Space Administration, and Administrator Griffin stated that one of the most important aspects of his trip is the opportunity to gain better transparency and trust.

Popular Mechanics recently reported that an Arms and Strategic Technology Investigations Unit of the Bureau of Immigration and Customs Enforcement uncovered a plot by an individual working for China's People's Liberation Army to purchase an F110–GE–129 afterburning engine built by General Electric to power the F–16 at speeds greater than Mach 2.

What are NASA's concerns with respect to China's ability to reverse engineer some of our most sensitive technologies from satellites to engines to entire planes, and to what extent are the U.S. and China developing a relationship with respect to aeronautics research and development?

Dr. PORTER. Well, I would like to speak to that in regards to aeronautics, and there, we don't have any planned partnerships with the Chinese at this time for our hypersonics or anything else.

Mr. FORBES. Do we have any concerns about their re-engineering or reverse engineering some of the equipment that they are purchasing, and using that to our disadvantage?

Dr. PORTER. I am not really an expert in that, so I——

Mr. FORBES. Okay.

Dr. PORTER.—would rather not answer that.

Mr. FORBES. The second question I have is the NASA authorization bill directs the Administration to develop a national aeronautics policy by the end of 2006, to guide NASA's aeronautics research program. What kind of investment will NASA have to make in the coming years to ensure that this policy is a blueprint, rather than simply a wish list?

Dr. PORTER. The policy, of course, is, as you said, targeted for signature or completion in December, so until then, I can't comment on the details, but the policy itself will not comment on specifics of budget, of course, because there will be a Presidential policy.

I think what we have put together, as far as a program, is very much of the nature that would be aligned with, hopefully, what you will see, but we will have to wait until December.

MORE ON THE FUTURE OF AERONAUTICS

Mr. FORBES. Okay. And last question on this round, the 2002 NASA Aeronautics Blueprint, the 2002 Report of the Commission on the Future of U.S. Aerospace Industry, and the 2005 National Institute of Aerospace Report conclude that U.S. competitiveness in the aerospace industry is in jeopardy without a substantial, long-term, sustained investment in aeronautics research. The National Research Council's report titled *"Aeronautics Innovation: NASA's Challenges and Opportunities,"* and the 2006 *Decadal Survey of Civil Aeronautics* makes recommendations to accelerate NASA's aeronautics program. Where will the focus on fundamental aeronautics take us in the next five, ten, and twenty years?

Dr. PORTER. The intention of the program is to ensure that, in fact, we do address those concerns that were raised both in the Walker report and previous NRC reports, and the NIA report that you mentioned. All of those reports were part of what informed our thinking on how we restructured the program, and there was a consistent message in all of those reports regarding the importance of getting on the cutting edge, making sure we have a long-term focus in our research.

Indeed, because of some of the issues that the General raised regarding the need for the government to take that role, because industry has different challenges associated with being able to take a long-term strategic approach, where the government does well there. So, what you are going to see is a program, or what we have put together, we think as a program, that addresses those fundamental challenges, that answers, or tries to answer those really hard questions that we need to answer across the breadth of our portfolio, so that we can truly make revolutionary advances in aerospace, in air safety, and of course, in the performance and the reliability, and the fuel efficiency and the emissions and noise characteristics of those vehicles that will fly in the future.

Mr. FORBES. Thank you, Mr. Chairman.

Chairman CALVERT. Thank the gentleman. Mr. Miller, you are recognized.

HUMAN FACTORS IN RESEARCH

Mr. MILLER. Thank you.

Dr. Porter, one of the observations of the report was that the airline industry had depended greatly on NASA for research into aviation safety, as it was affected by human factors, and expressed the concern that a substantial loss, which the cuts have led to, in expertise at NASA, and at universities doing research for NASA, in human factors, would affect airline safety.

Is that a finding that you embrace, and what are your recommendations?

Dr. PORTER. I think it is a finding that is actually misinformed, and let me explain why.

Previously, there was a program, or I should say a project, that was called Human Measures and Performance, and what we did when we restructured the program was to ensure that the human factors research we conduct is integrated into our research in aerospace and in safety both. So, we have very strong human factors research components in both of those areas, but they are integrated into the research, rather than being isolated and separated, so there—so that particular project went away, and I think some people misinterpreted that therefore, our commitment to human factors research went away, when in fact, it is still a very strong commitment in both safety and in the aerospace systems program.

Mr. MILLER. General Hoover, what is your view on that?

Major General HOOVER. Well, we had a very strong, I would say advocacy for human factors within our committee, and had very serious debates. We ended up not identifying specifically a human factors research area, if you will, but rather, numerous other applicable research undertakings that supported the human factors issues.

I think it is important, and I know that NASA has had, in the past, a strong tradition of involvement in human factors, particularly out at Ames, and I think it is an area that, in various ways, needs to be supported.

Mr. MILLER. Dr. Porter, General Hoover just mentioned Ames, and said that was where most of the human factors research has been focused. I understand that just in the last budget year, we have lost 15 percent of the experts at Ames, who were actually NASA employees, and 70 percent of contractors and academics who were studying human factors. I am sure you remember that one of the criticisms in the investigation of the last Shuttle disaster was that so much of the expertise had been contracted out that there were not enough experts walking the halls, brushing shoulders with each other, talking to each other, and there was simply a lack of a collection of experts, and that that was a problem for NASA in recognizing problems.

Are you concerned that the loss of experts from Ames, where they are doing research into new procedures to avoid, or new technologies to avoid human error, human factors that threaten airline safety or aviation safety, will actually be a problem for the airline industry and others, simply not having access to experts that they need?

Dr. PORTER. Sir, I would reiterate my point that human factors is still a very strong element of my aviation safety program, and of course, a lot of that expertise does reside in Ames. I agree wholeheartedly with that observation.

Mr. MILLER. Is the information that I have that 15 percent of the experts have——

Dr. PORTER. That I would have to go back—I would have to take that question for the record, and confirm your numbers, because I don't have those specific to the human factors in front of me.

Mr. MILLER. Okay. Because the information I have is that 15 percent of the NASA employees who were experts in human factors are gone, and that 70 percent of the contractors and academics are gone.

Dr. PORTER. Well, I can tell you that the NRA that we released, which is, of course, was targeting academics and companies that conduct cutting edge research, did have human factors elements in them, so certainly, we are reaching out to universities that conduct that research.

But I can't comment on the specific numbers, because I just don't have those in front of me, but I will take your question for the record.

Mr. MILLER. General Hoover, I understood your answer to the last question was that you did not—that you agreed with your report, not with the agencies NASA's response to the report. Is my concern about the lack of experts simply being together, having kind of a critical mass of expertise, is that a problem for aviation safety?

Major General HOOVER. Mr. Miller, I don't know that I can really answer that question. As I said, it is difficult, because NASA's program has been evolving, and we—and the committee I was on really didn't have that kind of interaction with the NASA programs. They wanted us to take an independent view, and in our research and technology challenges that we have identified, I think there is a strong case made, in various of those challenges, about the importance of human—things that contribute to the human factors issues that you have raised.

Chairman CALVERT. I thank the gentleman. Mr. Diaz-Balart, questions. Mr. Hall.

DEMONSTRATIONS AND EXPERIMENT

Mr. HALL. Thank you, Mr. Chairman.

Dr. Porter, you seem to suggest that NASA finds not a heck of a lot of value in doing demonstrations. Do I read that correctly?

Dr. PORTER. In the testimony, I tried to address the distinction between a demonstration and an experiment, and if you don't mind, I would like to elaborate a little on that to clarify.

Mr. HALL. All right.

Dr. PORTER. We have been talking a lot today about the challenges in aeronautics that we face as a nation, the challenges in the airspace, the NGATS vision, and I don't like to use clichés, but in this case, it applies. That is a true paradigm shift for where we are today versus where we are trying to go.

The challenges the DOD faces are really large and looming, and require a lot of cutting edge, and of course, the challenges within the Vision for Space Exploration as well. So, as we look to the future, we have two paths we can do down.

One is to take the near-term, incremental approach, and to continue doing what you already know how to do, and to keep doing things that you feel comfortable with, and you keep working, and you get a little bit better each time. And that is the realm of demonstrations, where you are pretty sure you already know, and then, you are out to prove that you are right.

The other path is to say we have to go after what we don't know. We have to pursue the unknown. We have to explore, and we have to be willing to take risks, because the kind of future we are envisioning requires that kind of commitment. It requires taking big leaps in our knowledge and understanding, so that we can generate innovation, we can generate revolutionary capabilities. That is the realm of experiments, and there is a difference between experiments and demonstrations, and in experiments, you are pursuing the unknown. You are not trying to prove you are right, you are trying to find out where truth lies, and how to use that to get much better.

And that was the distinction I was trying to make.

Mr. HALL. Well, to look back a little bit, for a long time, the level of federal investment in civil aeronautics research and development has been going downhill, declining, and aeronautics is working in a tough budgetary climate right now, and it would be my guess, based on headlines and news reports, that we are headed for more problems budget-wise, as long as the war exists, and we have the outgo that we have right now, and in that situation, our chairman, Mr. Calvert, asks you to compare the recommendations of the reports with what you understand NASA is actually doing, and that is what you say, that is the demonstration part, and what they are actually doing, in its efforts to "reshape and strengthen."

Now, either one of those, for the path that you took to do the same as we are doing today, and improve little by little, that seems like that is the sure, certain path, but a little bit slower, that is your path of demonstration, but you say that we need to take risks with experiments.

I guess my next question would be absent demonstrations, how are you going to verify and validate new concepts? And aren't we really, when this good chairman asks you to reshape and to strengthen, you know, it is like in your own family, money ain't much, but it sure keeps you in touch with your kids. You are talking about money, are you not, to reshape and strengthen, almost first, to be able to do it, to carry out the experiments that you want? Experiment means you are experimenting.

Dr. PORTER. Right. So, your question was——

Mr. HALL. Well, you are giving me, how can you pursue your experiments by demonstrations? Keep what we have got going, and enjoy that, and appreciate that, and add to it, and be a little daring, but you have got to get the money to be very daring, because if you don't succeed, somebody has got to pay.

Dr. PORTER. So, the realm of the incremental approach, that is conducted very well, very successfully, very ably by industry, by the private sector.

The realm of the cutting edge is a very appropriate role for the government to play, and in the realm of the cutting edge, we conduct experiments. Now, in the pursuit of those experiments, we will ask the question, do we think we—do we have an idea that works? But the difference between a demonstration and an experiment is how you view how you set it up. In an experiment, it is okay if what you are doing doesn't work, as long as you report it accurately, and you provide the results to the community, and the community can therefore benefit from what you have learned. Some of the greatest successes in experiments are failures, in a sense.

Mr. HALL. Well, I used to be in industry, and a lot of times, we had to go to Prudential for more money on our loan, and I have had them tell me I listened to your ignorant proposal with an open mind. I don't—I am not saying that to you, because I have admiration and respect for you and your background, and an appreciation for what you are doing, but I wouldn't—I would go slowly on experiments, but I will read your testimony, and I have not read it in full, my folks have. I have always heard that: "Be not the first by whom the new is tried, nor yet the last to lay the old aside."

Can't we have some of both worlds?

Dr. PORTER. I believe that the realm of the government research is to ensure that we are pursuing the cutting edge, and getting after what we don't know in advancing our knowledge, so that we can really enable true creativity, true innovation, and true revolution that industry will enable to—be able to leverage and take forward to the commercial sector. And that will benefit everyone.

Mr. HALL. You give good questions. My time is up.

Chairman CALVERT. I thank the gentleman. Mr. Honda, you are recognized.

UNFUNDED PRIORITIES

Mr. HONDA. Thank you, Mr. Chair, and thank you, Dr. Porter, for coming back. Missed you the last time, so we appreciate this opportunity.

I am not full of homilies or sayings, but this—I need to just let you know that I do recognize that you are taking on a responsibility, a lot of which the issues, you have no—you had no impact on, that you have to work with what you got. It is like a seamstress, you know, rather than being given a bolt of silk, you are being given a bolt of raw wool, and they ask you to make a gown out of it, so——

But having said that, given the massive cuts that we have seen in the A in NASA, and I like to keep that A as much as possible in NASA, and then, there is some talk about some possible more monies coming through the appropriation process for this area of aeronautics, given the cuts that we have seen, what is it that you have in mind in how to use this possible $100 to $179 million of possible increase in the future.

Where would you use it and how would it be used?

Dr. PORTER. I don't think it is—you know, I don't like to deal with hypotheticals, so I don't think it is appropriate for me to comment on that.

Mr. HONDA. Well, let me ask you——

Dr. PORTER. The budget I have is what I have planned to, obviously.

Mr. HONDA. But we always have in mind what we want to put in if we have more. I am not asking you—I am not asking if this is what is going to happen, but what would be in your planning mind. I mean, you are an administrator.

Chairman CALVERT. If I could help the gentleman on that, Department of Defense, as the gentlelady knows, has their secondary list, or the list that is unfunded priorities.

Dr. PORTER. True.

Chairman CALVERT. And I think that that is the question that Mr. Honda is asking. If you, in fact, had a list of unfunded priorities, what would that list be? Is that an accurate portrayal of what you are saying?

Mr. HONDA. Possibly, right. If it is unfunded priorities, if the priorities mean that it would also look at the things that have been cut, I would like to know what that is.

Dr. PORTER. I think the best way to answer that question is to remember that regardless of whatever budget we are provided, we have established principles that are budget independent, and we do that intentionally, so that we could make consistent decisions. Regardless of budget, we will make decisions according to those three principles.

Mr. HONDA. Is there a principle that says we would like to bolster this portion of our program, if more money comes in, we will do that?

Dr. PORTER. Regardless of budget, whatever budget we have this year or any year, we will use those core principles, and then, we will use the process we have put in place, which I described, to put together the right answer. But the research portfolio that you see is according to those principles, and then, the budget is applied.

Mr. HONDA. Is there a priority in your head, as an administrator, that you would like to see? I heard your answers.

Dr. PORTER. Right.

Mr. HONDA. They are not satisfactory.

Dr. PORTER. Right.

Mr. HONDA. Well, all of us have some sort of idea what we would like to see come back.

Dr. PORTER. Right.

Mr. HONDA. Wouldn't you have any idea?

Dr. PORTER. I don't think it is appropriate to comment on things that are hypothetical at this point, regarding budget. I can tell you that what you see, in terms of the restructured budget, does represent our priorities, our commitment to a balanced portfolio in areas that address the needs of the future.

Mr. HONDA. I understand what you are saying.

Dr. PORTER. Right.

Mr. HONDA. But it is not the question I am asking. I mean, a balanced portfolio is a good policy, like a balanced budget with no deficit is a good policy, too. That is not reality, so, you know, I am not usually pushy, but you know, this is not a very satisfactory answer. In your position, you must have some idea—I am not asking you to—I am not telling you you are going to be held to it, and get crucified later, but you must have some sort of sense of which way the A in NASA will go if you had more funds.

Dr. PORTER. We will always pursue cutting edge, so whatever budget we have will be——

Mr. HONDA. Well, what is—well, the unfunded priorities, what are the top priorities in the unfunded list?

Dr. PORTER. We actually didn't create an unfunded priorities list.

Mr. HONDA. So, my chairman is wrong.

Dr. PORTER. He—no, he was citing the DOD as an example, I believe.

Mr. HONDA. I see.

Dr. PORTER. Right.

Mr. HONDA. So, you don't have any——

Dr. PORTER. Of budgets.

Mr. HONDA.—contingency plans, if in the event of more money coming down the tubes, would be available.

Dr. PORTER. We have a process in place that allows us to adapt to whatever budget we are provided, but the budget we have now allows us to execute the plans that we have.

Mr. HONDA. Where do you think that process will lead you to?

Dr. PORTER. What do you mean?

Mr. HONDA. What programs do you think that process will lead you to, applying the principles that you are talking about?

Dr. PORTER. The four programs that we have are already established, according to those principles that we talked about.

Mr. HONDA. And those four programs, would you help me again?

Dr. PORTER. The Fundamental Aeronautics Program, the Aviation Safety Program, the Aerospace Systems Program, and the Aeronautics Test Program.

Mr. HONDA. Okay.

Dr. PORTER. Which is the wind tunnels and propulsion tests.

Mr. HONDA. And of those four, there is not a priority which would go first, or you would——

Dr. PORTER. All four of those programs are important to the portfolio, yeah.

Mr. HONDA. Mr.——

Chairman CALVERT. If the gentleman would yield, I always remember the Under Secretary of the Army, Mr. Parker, our former colleague, and his unfunded priority list.

Mr. HONDA. Perhaps with the closing, I might want to ask Major General Hoover if he has any ideas.

Major General HOOVER. Well, sir, yes, I was about to jump in. I can appreciate Dr. Porter's position. I have been an Assistant Secretary, and I understand having to deal with budget realities, but I would suggest, for the benefit of the—of your committee, that the Decadal Survey itself provides a basis to determine what next priorities ought to be. Our methodology clearly lays out how we arrived at our priorities. If you have got more money, I think you can go to our report, and see the areas that would be next in line to fund.

I don't know whether Dr. Porter has the same view, you know, we can agree to disagree, but at least, there is a basis for the committee to examine where additional funding could be provided, or could be used.

Mr. HONDA. Thank you very much.

Chairman CALVERT. Thank the gentleman. Mr. Rohrabacher.

APPLIED AND FUNDAMENTAL RESEARCH

Mr. ROHRABACHER. Thank you very much, Mr. Chairman, and I apologize, as we have all had several meetings that we are supposed to be at at the same time, that I am a little late for this one.

Let me first of all ask whether or not NASA has any commitment at this time to developing new jet engines.

Dr. PORTER. We have a commitment to do research that should advance jet engine technology significantly, and in order to do that, we have to ensure that we are investing in research that allows us to do better with emissions, allows us to do better with noise——

Mr. ROHRABACHER. Right.

Dr. PORTER.—and allows us to do better with fuel efficiency.

Mr. ROHRABACHER. Is there a new jet engine, or is it just incremental improvements in current engines?

Dr. PORTER. It is neither. It is neither incremental, nor a particular jet engine, targeted toward a particular company. It is a breadth of core competencies in propulsion that we have to advance, particularly in noise, and also in emissions.

Mr. ROHRABACHER. Okay. So, we are talking about fundamental research, and not applied research.

Dr. PORTER. It is applied, but it is applied to the general concepts that have to be enabled, and yesterday, when I was at Glenn Research Center, one of the researchers presented a great example of that with the chevron nozzle, which is a nice example of a technology that came out of an idea, and an advancement of our understanding of how noise is generated, and how to mitigate against that. The chevron technology was then adopted by industry very quickly, very rapidly, once they realized that is a good idea.

Mr. ROHRABACHER. How long ago was that?

Dr. PORTER. That was in the mid-'90s, I believe, is when that research was conducted.

Mr. ROHRABACHER. So, it was over ten years ago, and you are talking about research that took place fifteen years ago.

Dr. PORTER. The research is continuing under the fundamental aero program. That particular research, we are continuing to do.

Mr. ROHRABACHER. So the research was begun over fifteen years ago, and is still continuing on that same item.

Dr. PORTER. There is a lot we still don't understand about the production of turbulence that leads to the noise that gets generated, so yeah, there is still a lot——

Mr. ROHRABACHER. There is also——

Dr. PORTER.—to be done.

Mr. ROHRABACHER. There is also to be said something about a project that never ends.

Dr. PORTER. Absolutely. You don't keep doing something——

Mr. ROHRABACHER. Right.

Dr. PORTER.—just because you want to keep doing it. I couldn't agree more.

Mr. ROHRABACHER. That is right. Right. Do you think——

Dr. PORTER. But in that particular case——

Mr. ROHRABACHER. Do you think NASA has any kind of problem that way, that they just, you know, that they just keep studying something, and studying something, and——

Dr. PORTER. The research portfolio that we are doing is not studying something for the sake of studying it. It is driven by system level challenges that we feel are critically important.

Mr. ROHRABACHER. Okay. Let me note that applied science is much different than fundamental research science, and I think

NASA has gone, in the last thirty years, from being something where they are trying to put things together, and make things happen, to being a research organization, which could well be done in the private sector by universities and others, rather than government employees.

And in terms of actually trying to push towards a more—applying something, getting something tangibly done, and then, moving on to the next project, which is what happens when you apply things, I have noticed that NASA now, in some areas, is moving towards the X Prize concept, and that is, I guess, part of what they call the Centennial Challenge, but only one of these prizes has anything to do with advancing aviation, the rest of them are space-related prizes.

Dr. PORTER. If I could address a couple of your points, I would say that fundamental research, in the way that we mean it in aeronautics is not basic research, and you will note that I have never actually used the term basic research, and I do that intentionally, because fundamental research, the way we mean it, means advancing our knowledge and understanding in the underlying principles, and then, integrating that knowledge to the system level.

So, what we do is not just for the sake of doing it, but rather, driven by system level challenges, like noise, like emissions, okay.

Mr. ROHRABACHER. I am just—yeah, I understand what your wording is——

Dr. PORTER. So——

Mr. ROHRABACHER.—and I would like to say that——

Dr. PORTER. So, that is actually applied research——

Mr. ROHRABACHER. Yes. Yes.

Dr. PORTER.—is what I am getting at.

Mr. ROHRABACHER. I understand, and when government officials are too concerned about wording, you know that something is really wrong——

Dr. PORTER. Well, I am concerned——

Mr. ROHRABACHER.—just so you——

Dr. PORTER.—that it was characterized as not applied.

Mr. ROHRABACHER. Yeah. I——

Dr. PORTER. And so, it is.

Mr. ROHRABACHER. I understand you are very good with words, and so am I, but your job in NASA is not to be good with words. It is to be good with technology.

Dr. PORTER. Right.

Mr. ROHRABACHER. And it is to be good with building things and getting things done——

Dr. PORTER. Sure.

Mr. ROHRABACHER.—rather than studying things to death, and let me note that I don't think we are getting our money's worth out of NASA. I think that NASA has become too study oriented, too research oriented, and not doing things enough oriented, and when it does things, it tends to be enormously expensive, as compared to the private sector.

Back to the X Prize, you were going to say that, something about the X Prize. Is my wording wrong when I say that only one of the X Prize concepts has something to do with aviation-based technology?

Dr. PORTER. I would have to double check that. I will take that question for the record.

Mr. ROHRABACHER. All right. So, and if it is—if the analysis I am giving you is correct, wouldn't that suggest maybe there is a little imbalance going on there, in terms of emphasis?

Dr. PORTER. Not necessarily. I would have to take that question for the record.

Mr. ROHRABACHER. All right. Are you a lawyer, by the way? I just——

Dr. PORTER. No, sir.

NASA AND CHINA (CONT.)

Mr. ROHRABACHER. All right. Okay. Let me ask you about something else. I happen to have with me, Mr. Chairman, and I would like to submit these two articles for the record, an article from Defense News, current article, it talks about China trying to blind U.S. satellites with lasers, China trying to destroy our space-based assets. Sunday, we have a story in the New York Times talking about NASA head, NASA chief heads to China to discuss space cooperation.

Is there something contradictory about this situation?

Dr. PORTER. Sir, I am here to represent the Aeronautics Research Mission Directorate, and as I explained earlier, aeronautics has no partnerships planned with China.

Mr. ROHRABACHER. All right. I just wanted to make sure we got that on the record, because this is a hearing about NASA, and I understand that is not your area of responsibility.

You think that—is there any worry about the Chinese benefiting from the research that we do in avionics?

Dr. PORTER. The Chinese benefiting from the research we do in avionics?

Mr. ROHRABACHER. Right.

Dr. PORTER. The Chinese are, obviously, going to research in many areas. They are going to conduct their own research, and pursue——

Mr. ROHRABACHER. Right. And they are going to take advantage of ours as well, if they can.

Dr. PORTER. I wouldn't presume to speak for the Chinese and their intentions.

Mr. ROHRABACHER. All right. Well, I am just putting this on the record that, Mr. Chairman, I am very concerned both with our public sector and private sector. We should have learned ten years ago, when the Chinese were given technology that was developed by hundreds of millions of dollars, if not billions of dollars of U.S. research, were given technology that has permitted them to have capabilities in the area of rocketry that the U.S. taxpayer paid for.

I hope we never duplicate that, in terms of avionics, where our corporations, as the corporations ten years ago gave missile technology away, I am hoping that, in order to sell airplanes, that we don't give technological capabilities to the Chinese in terms of avionics as well, and I just want to be on the record as stating that as a concern.

Thank you very much.

Chairman CALVERT. On behalf of Mr. Rohrabacher, I am sure we apologize for accusing you of being an attorney.

Dr. PORTER. Thank you.

Chairman CALVERT. Except for Mr. Forbes here.

Dr. PORTER. One of the harshest things anyone has ever said to me, actually. I am just kidding.

Chairman CALVERT. I can understand. And I was also surprised that Mr. Rohrabacher read the New York Times, but——

Mr. ROHRABACHER. Let me note that when I ran for office the first time, the most—I would say the most useful slogan I used in my campaign was "Vote for Dana: At least he is not a lawyer." So, there you go.

INDUSTRY PARTICIPATION

Chairman CALVERT. Okay. Okay, back onto Dr. Porter.

In developing your research program, why does NASA exclude industry from participating with your scientists at the very first step, to help draft the ten year roadmap? Don't you think that industry's views should be of value at NASA at the earliest steps, instead of asking them to respond to a plan, rather than on the back end? Wouldn't it be best if industry was involved? Aren't they just as capable of coming up with new ideas, new concepts, and allowing them to sit with you, and research—talk—when you are talking about these research roadmaps, and maybe they will come up with some good ideas to be pursued?

What was wrong—what is wrong with that?

Dr. PORTER. Industry's participation is very important, and the reason we used an RFI was because we wanted to ensure that everyone felt they had equal opportunity to express their views. So, we didn't want to have a perception that certain companies had inroads with us to express those views, and it was the way that we wanted to ensure everyone had equal access. So, we—that is why we got so many responses. Now, when we got those responses, we used those responses as part of the formulation process.

Chairman CALVERT. I would—as long as it is a transparent process, you know, I mean, I know that we got accused, when we put the energy bill together, it was a nontransparent process when industry was involved, but if it is a transparent process, where industry was involved in the beginning, rather than in the end, where many would think that they were excluded from the most important part of the process, it might be something that you ought to consider in the future.

Dr. PORTER. Right. I am just—I agree with you that industry should be included, and by the way, they shouldn't be included just once, and so, one of the messages I am trying to convey is that we continually have meetings with industry, but also, participation in our programs.

So, what we are trying to do is encourage, through Industry Days, for example, companies to come onboard, participate in our technical working groups, provide technical as well as management, as well as strategic inputs on what we are doing, and do that in a manner that allows us to adjust and adapt, so we will do annual program reviews, where we have external experts come in, and assess where we are, and ask are we doing the right things.

Chairman CALVERT. Appreciate it. General Hoover, do you have any comment on that?

Major General HOOVER. Well, I think the, maybe the litmus test about partnerships with industry, and developing views with industry, is will they, in fact, bring serious resources to the table on their own in those partnerships, and I think that remains to be seen. I don't know what the kinds of responses that NASA has received to their proposals, but I think it is too early to tell.

Clearly, we developed our committee's report, sort of using the other way around, as you suggested. We had a wide range of university, industry, former government officials, that were put together with a great concern for balance of views. Sure, there are biases, people have their own view of this and that, but we put together a committee that we believe balances biases, and people had to be able to stand up and be counted, in terms of putting forth whatever their view of a particular technology was.

And so, I think, you know, we did go through that front end process, and it was done with—in the absence of what NASA was doing, because Dr. Porter wanted independent, objective advice.

Chairman CALVERT. Any additional questions? Mr. Udall.

Mr. UDALL. Thank you, Mr. Chairman.

BUDGETARY ADVICE PROCESS

I must observe that without Judge Hall and Dr. Rohrabacher, this committee would not be the interesting place that it is to serve, and I would offer to my friend and colleague from California, the well-known surfer, Congressman Rohrabacher, that there are support groups for those who continue to read the New York Times when advised to not do so, and we would be willing to work with you in that regard.

And Judge Hall connected me immediately with my college age son, when he talked about money as not all things, but it does keep you in contact with your children, and I thought about that as a corollary, Dr. Porter, and I thought if the aeronautics branch of NASA had more money, it might keep you better in touch with industry and academia, and I understand your unwillingness to respond to Congressman Honda's questions, but I do know there are many of us here that are going to try and find some additional resources for the aeronautics side of the house at NASA, and I would look forward to having that conversation with you if, in fact, that money is forthcoming.

If I could, let me move to NGATS, and given the importance your testimony attaches to that interagency effort, it doesn't appear to make much sense for NASA to be cutting its funding for aerospace systems research from $120 million in '07, fiscal year 2007, which represents, by itself, a $54 million decrease from the '06 level, to a level of about $90 million in fiscal year 2011. Even excluding the loss in purchasing power due to inflation over the next five years, this seems ill advised, and that leads me to my question, two questions, actually.

What guidance, if any, did you receive from the interagency Joint Planning and Development Office, the organization charged with developing NGATS, that gave you the confidence you could cut NASA's aerospace systems budget by that amount over the next five years, and if you didn't receive any specific budgetary advice or guidance from JPDO, what was your basis for making those cuts?

Dr. PORTER. I would like to make a couple of points to answer your question. First of all, I think this committee understands, but it is important, our support for the NGATS is not just in the Aerospace Systems Program. So, the Aerospace Systems Program targets the air traffic management piece.

As you know, the JPDO has recognized eight thrust areas, eight IPTs, they call them, that all have to be addressed to really advance the next generation. One of those is the agile air transportation system, that is the air traffic management piece. There is also, obviously, it goes without saying, a safety element. So, our Aviation Safety Program also provides important research.

And there is also the environmental IPT, which of course, as you well understand, is critical, because if we double or triple the capacity of the air traffic management, and do nothing about the vehicles that are going to reside there, that is a theoretical exercise. You have got to be able to advance the capabilities of the vehicles.

So, our portfolio represents a balance, to address all of that. So, in our fundamental aero, subsonics fixed-wing in particular, we are really targeting hard those noise and emissions challenges that have to be addressed. In the safety program, we are looking toward the future of the vehicles that are going to reside in that system ten, fifteen, twenty years down the road, and then, the aerospace systems targets that air traffic management research.

Now, the way we put the proposals together, and I did allude to this, so I will be a little repetitive here, but we did use an external subject matter expert review process, where we asked folks from the JPDO in particular, and the airspace management, excuse me, Aerospace Systems Program, to review what we had proposed to do.

And given that part of the review process, and it was a multistage process, where the researchers had to go back and make changes and adjustments, according to that feedback, and come back and make sure that what they were doing made sense to that panel of experts, we feel that we put together a proposal, excuse me, a portfolio that really does represent the best that we can do, and support air traffic management and safety and environmental challenges. And NASA really does need to take the lead in the cutting edge in all of those areas on behalf of NGATS.

Mr. UDALL. I appreciate all of that background, but I don't know that you have answered my question about whether there were any budget—there was any budgetary advice, and if there was not——

Dr. PORTER. Okay.

Mr. UDALL. You made the decision based on your own thinking or your own analysis.

Dr. PORTER. The—one part of the analysis, of that external review process, was resource plans, so they looked at our resources, and the resources included personnel dedicated, and facilities dedicated, so they did look at what we had planned to do the work that we felt was most relevant.

Mr. UDALL. Is they the JPDO?

Dr. PORTER. It included the JPDO, FAA, NOAA, who was also involved, the weather folks.

Mr. UDALL. But in the end, are you—you are making this decision based on what you think is important, not necessarily working with this interagency working group?

Dr. PORTER. Actually, I took the recommendations from the panel of experts that reviewed the proposals, and that was how we—so I was, you know, you could sort of imagine me as like a source selection authority on the review panel, if you will, where they were presented to me as this is the final——

Mr. UDALL. My——

Dr. PORTER. I am sorry, I don't think I am answering your questions.

Mr. UDALL. My concern is that you have got a proposal, but then, you also have budgetary levels, and they are mutually reinforcing, but——

Dr. PORTER. Right.

Mr. UDALL.—with these kind of budgetary cuts, that seem to be looming, I am concerned, as the General pointed out, this is not the next Next Generation Air Traffic System, it is the next air traffic system, and I am concerned that we are going to hamstring ourselves, and not actually be able to implement it, given these numbers.

Dr. PORTER. There are, of course, five agencies that are contributing, so NASA is not the only one, and I would point out that for the implementation portion that you are referring to, that is the FAA's role, so NASA's role is to provide the research. The FAA's role is to implement. So——

Mr. UDALL. With all due respect, I am not sure I am getting the answer I would like.

Dr. PORTER. Okay.

Mr. UDALL. But if I could turn to General Hoover for his comment——

Dr. PORTER. Okay.

Mr. UDALL.—and then, I see my time has expired, but——

Dr. PORTER. Sorry.

Mr. UDALL.—I think this is an important——

Dr. PORTER. Okay.

Mr. UDALL.—subject. General, would you care to comment?

Major General HOOVER. Well, I can't comment on the impact of what NASA has done in reducing their budget, other than the National Research Council has been working with the JDPO now for some time in reviewing its plans and making inputs.

I guess I would obviously feel that a cut in—would be a reduced effort, in some part, in some way, but I don't really have any insights, no.

Mr. UDALL. Thank you. To be continued.

Chairman CALVERT. Well, I am going to—unless there is further questions, I think we are—Mr. Rohrabacher, you have an additional question?

REIMBURSABLE FUNDING

Mr. ROHRABACHER. How much does NASA receive from fees that we use, that we receive from providing testing and other types of help to the private sector companies?

Dr. PORTER. That is a good question. You are talking about reimbursable, what we call NASA reimbursable funding.

Mr. ROHRABACHER. Right. Like, for example, when I went up in Northern California there, and saw this, the wind tunnel, and——

Dr. PORTER. Sure. Absolutely.

Mr. ROHRABACHER. How much does NASA receive in money from these type of services that we offer the private sector?

Dr. PORTER. I don't have those numbers in front of me, so I will have to take that for the record, and get that number back to you, okay?

Mr. ROHRABACHER. I think it is, is it significant, insignificant? Does that wind tunnel, for example, pay for itself?

Dr. PORTER. That is a good question, but I don't want to answer that, and give you the wrong answer. I would rather take it for the record.

Mr. ROHRABACHER. And again, for the record, Mr. Chairman, you know, when we go, come into a period of budget restraint, and as we are now, and we want to accomplish things, if we are doing services, if, as you were suggesting in your answer to my first time of questions, maybe it is also time that we make sure that the private sector is actually compensating us for the services that are being provided, so that we can maintain our level of spending on other areas of concern, and——

Chairman CALVERT. I would just point out to the gentleman.

Mr. ROHRABACHER. Yes.

Chairman CALVERT. We went through that discussion on the ETRAP cost return on services provided by the government. There are times, in fact that the—you cannot receive a true cost relevant to the capital investment in some of these projects which were enormous, that were done for purposes that were outside of—that private industry would never invest, and so, we—I think the Centers have done an excellent job of coming with an overhead cost number at each Center, to charge various industries and so forth, universities, a reasonable amount of money, to the degree that they will use those facilities.

We found that when we had a problem with the tunnels, especially, they were not being used at all, and in fact, Boeing and Lockheed-Martin went to Europe to test their, use their air tunnels for the F–22, our own fighter, which would risk losing, obviously, we would not want to lose classified information being transferred over to others.

So, there is a practical level that you can charge in a business environment which they will pay, and so, that has to go into it. And so, I think that they have done a pretty good job of rationalizing that out, and I think that the tunnels now, in the United States, are being more utilized than they were before, is that correct, Doctor?

Dr. PORTER. I think you are going to see that more in the future. We have just started these changes. As you know, the agency took stewardship of those, so we will see how that plays out in the coming years.

Mr. ROHRABACHER. And we will be watching. Thank you very much.

Chairman CALVERT. Thank the gentleman. If there is no further questions, I want to thank the witnesses for coming today. I know that there is another process that wasn't mentioned, to get money into aeronautics, and that is called earmarking, which is kind of controversial right now, but our friends on the other side of, a hundred yards from here, use that process to a fare-thee-well, so that may, who knows, may be visited upon us.

With that, we adjourn.

[Whereupon, at 11:39 a.m., the Subcommittee was adjourned.]

Appendix 1:

Answers to Post-Hearing Questions

ANSWERS TO POST-HEARING QUESTIONS

Responses by Lisa J. Porter, Associate Administrator for Aeronautics, National Aeronautics and Space Administration (NASA)

Questions submitted by Chairman Ken Calvert

Next Generation Air Transportation System

Q1. The out-year numbers in your FY 2007 budget request for Airspace Systems drop 25 percent (between FY 2007 and FY 2011) at the same time that the Joint Planning and Development Office (JPDO) is expected to ramp up spending on Air Traffic Management (ATM)-related technology development and demonstration projects. What is the rationale for reducing the level of investment? Will NASA's proposed ATM-related research jeopardize the JPDO's ability to develop the Next Generation Air Transportation System on schedule? Is the Airspace Systems funding profile fully consistent with the JPDO's plans and programs?

A1. NASA's research portfolio has been constructed according to the following three core principles: 1) we will dedicate ourselves to the mastery and intellectual stewardship of the core competencies of aeronautics for the Nation in all flight regimes; 2) we will focus our research in areas that are appropriate to NASA's unique capabilities; and, 3) we will directly address the fundamental research needs of the Next Generation Air Transportation System (NGATS) while working closely with our agency partners in the Joint Planning and Development Office (JPDO). As such, these principles are what provide the rationale for the prioritization of our research.

Our commitment first and foremost must be to provide the mastery and intellectual stewardship of the core competencies of aeronautics for the Nation. These core competencies include those relevant to ATM research, of course, but they also include a large number of other critical competencies that are addressed in our Fundamental Aeronautics and Aviation Safety Programs. Our research must focus on areas appropriate to NASA, which means that we are phasing out work in the Airspace Systems Program that is near-term, incremental research as well as prototyping and operational development. Finally, our commitment to addressing the fundamental research needs of the NGATS requires a balanced research portfolio that draws upon our NASA-unique capabilities to address ATM, environmental, efficiency, and safety-related research challenges, all of which must be worked in order for the NGATS vision to be realized.

Regarding the NGATS schedule and JPDO's plans and programs, it is important to note that the Enterprise Architecture, the Operational Improvement roadmaps, and the Integrated Capability Work Plans are still being developed. These activities are planned to be settled during FY 2007, and until these activities are finalized and agreed upon by all JPDO members, we prefer not to speculate about how our programs will specifically align with the finalized JPDO plan. We can state, however, that our research portfolio has been guided by the required capabilities articulated in the NGATS vision, and our proposed research in ATM was reviewed and approved by several external Government experts, including members of the JPDO, the Federal Aviation Administration (FAA) and the National Oceanic and Atmospheric Administration (NOAA).

Finally, we would like to point out that our research portfolio aligns very well with the recommendations of the NRC Decadal Survey, which was conducted completely independently of our own restructuring. Forty-seven of the 51 technical challenges recommended by the NRC are currently present in our restructured portfolio (see attached cross-walk matrix). We believe this is a strong affirmation that we are focusing our efforts on the proper research areas, not only in ATM research, but also across our entire portfolio.

Space-Related Research

Q2. The Decadal Survey *categorizes the space program as a "lower priority Strategic Objective" for civil aeronautics research. Do you share that view? What percentage of resources do you plan to devote to space-related research and for what topics? Does hypersonics fall within your meaning of space-related research?*

A2. The 51 Technical Challenges and Five Common Themes identified in the report are closely aligned with ARMD's restructured research portfolio. However, we believe that attempts to try to stovepipe aeronautics research into 'civilian aeronautics' versus 'space-related' are shortsighted and ignore historical fact.

NASA's aeronautics research has historically played and will continue to play a vital role in space exploration. Advances in our fundamental knowledge and understanding in aerodynamics, aerothermodynamics, flight dynamics and control, materials, structures, and human interface technologies like integrated cockpit panels have been critical to the success of NASA's space program over the past several decades. As we look to the future challenges in space exploration, we recognize the need to greatly advance our fundamental understanding in key aeronautics disciplines across all flight regimes in order to advance our capabilities for safe flight through any atmosphere, be it our own, or that of another planet.

We do not typically parse our portfolio into "space-related" and "non-space-related" research, because a large portion of the research that we conduct in the Fundamental Aeronautics and Aviation Safety programs benefits both the civilian aeronautics and space exploration communities. For example, advances in computational fluid dynamics modeling and lightweight high-temperature materials will be critical to successfully achieve reduced drag and improved engine performance on future air vehicles. But they will also be critical for the design of future space vehicles. Similarly, advances in integrated vehicle health management, flight deck technologies, and resilient aircraft control will be critical for the safety of the future fleet in the airspace, but such advances will also likely be of great value to future space vehicles. About 20 percent of our research in both supersonics and hypersonics targets challenges associated with entry, descent, and landing that will ultimately benefit both robotic and human space exploration.

However, the focus is not necessarily on either space or atmospheric flight, but rather on the generation of knowledge that can impact both.

To address the specific question about hypersonics, our research portfolio in hypersonics is designed to advance our nation's mastery of flight at very high speeds. As with other elements of our research portfolio, the beneficiaries of this research include our partners in space exploration, our Defense Department (DOD) partners, and members of the private sector, many of whom believe that there is a potential future commercial market in hypersonics. Fundamentally, our commitment to hypersonics research stems from our commitment to pursue the frontiers of flight for the Nation. And that frontier does not stop at Mach 1. We must continue to push the envelope of that frontier, and we must do so with an awareness that other nations share similar aspirations.

Transitioning Technologies

Q3. The Decadal Survey *urges NASA to "develop each new technology to a level of readiness that is appropriate for that technology. . ." At our July hearing on NASA's Aeronautics program, the National Academies' witness stated that NASA should conduct technology demonstrations on a limited basis. What are NASA's plans for transitioning technologies? Will there be instances where NASA develops promising technologies to a level ensuring transition to industry or government?*

A3. NASA believes in focusing on "knowledge transition" rather than "technology transition." Focusing on "technology transition" tends to drive one to focus on devices and widgets, rather than on the knowledge that enables their creation. In order to ensure that what we do benefits the community broadly, we have to ensure that the knowledge and understanding that underpins any new technology is transferred to the community in such a way that that technology can be broadly applied. If we do not do this, the device or widget becomes a point-design that is only of value to the small number of users that were directly involved in "demonstrating" it on a specific platform. A relevant historical example of successful knowledge transition that resulted in a revolutionary impact on the entire aeronautics community was the invention of the engine cowling in the late 1920s. The development of the cowling was not about the development of a "device;" rather it was about improving our knowledge and understanding of aeronautical design. Designers could not simply stick an engine cowling on an aircraft and expect it to work. They had to specially design a cowling for each aircraft. To do that, they had to understand the principles behind the operation of the device. The National Advisory Committee for Aeronautics (NACA) provided that understanding, and made the results immediately public by means of a NACA Technical Note so that industry could benefit, which they readily did.

NASA intends to disseminate the results of its research as broadly as possible and in as timely a manner as possible by publishing our results in peer-reviewed journals and NASA Technical Reports. Furthermore, we will establish technical working groups within each project to engage industry and academic partners on a regular basis in order to facilitate knowledge transfer. Space Act Agreements will also be used to establish intellectual partnerships with industry that enable NASA to leverage industry's unique systems-level expertise while enabling industry to quickly acquire research results and establish close working relationships with the researchers both internal and external to NASA who contribute to the research.

Ultimately, however, it is up to each company to decide for itself whether to invest in the development of particular concepts and technologies. Removing most or all of the risk for industry to do that removes the influence of market economics. This is indeed a significant distinction between us and other countries. NASA believes that the free market is the best determination of what technologies should be developed for commercial application, not the government.

Q4. Your statement makes clear that NASA finds little value in doing demonstrations. Absent NASA demonstrations, how do you expect new concepts to be verified and validated?

A4. The statement is intended to make a clear distinction between demonstrations and experiments. Demonstrations set out to prove that a concept or technology works; experiments set out to pursue technical truth, which is critical to ensuring adherence to the scientific method.

New concepts must be tested, but they may not work. Verifying concepts rather than testing them drives us to demonstrations rather than experiments. If we focus on demonstrating that we are right, then we are not on the cutting edge of research; we are simply doing what we already know how to do. That is not the appropriate role for NASA's aeronautics research. To pursue the cutting edge, we must test things that may or may not work as expected, and understand the results of the tests. Only through such experimentation will we learn to build what we cannot build today.

NASA will conduct experiments, both on the ground and in flight, to test out concepts, ideas, novel technologies, and to collect data that expands our knowledge and that allows us to develop better models, design tools, and databases.

Computational Modeling

Q5. The reshaped aeronautics research program relies heavily on computer-based and physics-based modeling. What is the state of maturity of computational modeling and simulation today at NASA? How long, and at how great of an expense, will NASA have to invest in these capabilities?

A5. Our vision of the future includes the ability to compute, from first principles, the behavior of the multiple components of a variety of aerospace systems and the interactions that take place among them. This future capability will allow us to guide the development of advanced technologies with significantly lower costs because of reduced testing requirements. In addition, this new generation of computer-based modeling tools will allow us to credibly assess new technologies and concepts in flight regimes where it is either impractical or impossible to conduct validation experiments. NASA has been a leader in the development of the first generation of such tools and will continue to innovate in order to advance the state of the art. This first generation of computational tools has proven to be extremely useful in a variety of fields (structures, fluid mechanics, acoustics, material science, propulsion, etc.) but still relies heavily on experimental validation and calibration to be considered sufficiently predictive. Even with these shortcomings, however, the use of these tools is pervasive across the disciplines of engineering science and has been and continues to be a fundamental part of our research portfolio. In the coming years, NASA expects to continue to commit significant resources to the development of a second generation of tools that are truly predictive and physics-based. Work in physical models, multi-physics simulations, validation & verification, error estimation, numerical analysis, and uncertainty quantification will pave the way for the computational modeling of the future. We note that such a focus is in alignment with the recommendations of the NRC Decadal Survey. Furthermore, almost every company that we have engaged with during the past year has indicated that this is a priority research area.

We will continue to pursue this area of research for a very long time because, quite frankly, a sustained, long-term effort is required to make significant advances. We estimate that about 20 to 30 percent of our investment in Fundamental Aeronautics currently addresses this type of work. It is plausible that a slight increase in the next 10 to 15 years will make sense such that 35 percent or more of our efforts in Fundamental Aeronautics may be focused in this area 15 years from now. We also estimate that about 15 percent of our investment in Aviation Safety currently addresses this type of work.

Computer-based and physics-based modeling and simulation also play a critical in ARMD's Airspace Systems Program. The state of maturity depends upon the application being considered. For example, an important area that has achieved a high level of maturity is human-in-the-loop simulation of aircraft that operate in today's National Airspace System (NAS). The major investment that NASA will be making in computer-based modeling for this area is in the modeling of technologies both emerging and those that do not yet exist that are being postulated to provide significant improvement in capacity, efficiency, and safety of aircraft operating in the future NAS. By contrast, the area of computer modeling for multi-disciplinary system design that accounts for the physics and procedures for all the aircraft operating in the NAS is at a much lower level of maturity. In addition, computational modeling of the terminal airspace (within ~50 miles of an airport), where interactions need to be modeled between multiple aircraft as well as between aircraft and airports, is also at a low level of maturity. These areas will be a large focus of the Airspace Systems Program research.

The overall Airspace Systems Project investment in computer-based and physics-based modeling is approximately 20 percent of its portfolio. NASA will need to provide a continual, long-term focus in these areas because the JPDO will rely upon the knowledge, concepts and tools that will be generated as a result of this research to provide answers to the questions that need to be answered to achieve its vision of the NGATS.

Decadal Survey

Q6. How do you specifically plan to use the Decadal Survey *in your planning and budgeting processes?*

A6. We strongly agree with five Common Themes identified by the NRC and they are already present across our research portfolio, as discussed in the written testimony submitted for the record at the hearing held on September 26, 2006. As can be seen in the attached cross-walk matrix, 47 of the 51 Technical Challenges are also already well-represented in our portfolio. Given that the NRC conducted their study completely independently of our restructuring, we believe this is a strong affirmation of our newly-created program. ARMD does not intend to pursue the four challenges highlighted in red on the matrix. Item D10 was largely covered by the Unmanned Aerial Vehicles in the NAS project that NASA phased out and transitioned to the FAA in FY 2006, in accordance with the direction provided in the Conference Report (House Report 109–272) accompanying H.R. 2862, the FY 2006 Science, State, Justice and Commerce Related Agencies Appropriations bill. We note, however, that much of the research that we conduct in ARMD (e.g., noise reduction, emissions reduction, performance, high-lift, materials, aeroelasticity, flight control systems, safety, and trajectory optimization) will benefit both manned and unmanned aircraft. Item D7 is being addressed by the FAA, the DOD, and industry. Item A7a is being pursued by the DOD. While a couple of items listed under B9 are being addressed in our Integrated Vehicle Health Management project, ARMD will leave the majority of that activity to the Department of Energy, the DOD, and industry.

Cross Walk-Matrix Between ARMD Portfolio and Decadal Survey Technical Challenges

	A Aerodynamics and Aeroacoustics		B Propulsion and Power		C Materials and Structures		D Dynamics, Navigation, and Control, and Avionics		E Intelligent and Autonomous Systems, Operations and Decision Making, Human Integrated Systems, Networking and Communications
FA	A1. Integrated system performance through novel propulsion-airframe integration	FA	B1a. Quiet propulsion systems	AvSafe	C1. Integrated vehicle health management	ASP/ AvSafe	D1. Advanced guidance systems	FA/ASP/ AvSafe	E1. Methodologies, tools, and simulation and modeling capabilities to design and evaluate complex interactive systems
FA	A2. Aerodynamic performance improvement through transition, boundary layer, and separation control	FA	B1b. Ultraclean gas turbine combustors to reduce gaseous and particulate emissions in all flight segments	FA	C2. Adaptive materials and morphing structures	ASP	D2. Distributed decision making, decision making under uncertainty, and flight path planning and prediction	ASP	E2. New concepts and methods of separating, spacing, and sequencing aircraft
FA	A3. Novel aerodynamic configurations that enable high performance and/or flexible multi-mission aircraft	FA	B3. Intelligent engines and mechanical power systems capable of self-diagnosis and reconfiguration between shop visits	FA	C3. Multidisciplinary analysis, design, and optimization	FA	D3. Aerodynamics and vehicle dynamics via closed-loop flow control	ASP	E3. Appropriate roles of humans and automated systems for separation assurance, including the feasibility and merits of highly automated separation assurance systems
FA	A4a. Aerodynamic designs and flow control schemes to reduce aircraft and rotor noise	FA	B4. Improved propulsion system fuel economy	FA	C4. Next-generation polymers and composites	AvSafe	D4. Intelligent and adaptive flight control techniques	ASP	E4. Affordable new sensors, system technologies, and procedures to improve the prediction and measurement of wake turbulence
FA	A4b. Accuracy of prediction of aerodynamic performance of complex 3D configurations, including improved boundary layer transition and turbulence models and associated design tools	FA	B5. Propulsion systems for short takeoff and vertical lift	FA	C5. Noise prediction and suppression	AvSafe	D5. Fault tolerant and integrated vehicle health management systems	ASP/ AvSafe	E5. Interfaces that ensure effective information sharing and coordination among ground-based and airborne human and machine agents
AvSafe	A6. Aerodynamics robust to atmospheric disturbances and adverse weather conditions, including icing	FA	B6a. Variable-cycle engines to expand the operating envelope	FA	C6a. Innovative high-temperature metals and environmental coatings	ASP/ AvSafe	D6. Improved onboard weather systems and tools	ASP	E6. Vulnerability analysis as an integral element in the architecture design and simulations of the air transportation system
	A7a. Aerodynamic configurations to leverage advantages of formation flying	FA	B6b. Integrated power and thermal management systems	FA	C6b. Innovative load suppression, and vibration and aeromechanical stability control		D7. Advanced communication, navigation, and surveillance technology	ASP	E7. Adaptive ATM techniques to minimize the impact of weather by taking better advantage of improved probabilistic forecasts
ASP	A7b. Accuracy of wake vortex prediction, and vortex detection and mitigation techniques	FA	B8. Propulsion systems for supersonic flight	FA	C8. Structural innovations for high-speed rotorcraft	AvSafe	D8. Human-machine integration	ASP	E8a. Transparent and collaborative decision support systems
FA	A9. Aerodynamic performance for V/STOL and ESTOL, including adequate control power		B9. High-reliability, high-performance, and high-power-density aircraft electric power systems	FA	C9. High-temperature ceramics and coatings	AvSafe	D9. Synthetic and enhanced vision systems	ASP/ AvSafe	E8b. Using operational and maintenance data to assess leading indicators of safety
FA	A10. Techniques for reducing/mitigating sonic boom through novel aircraft shaping	FA	B10. Combined-cycle hypersonic propulsion systems with mode transition	FA	C10. Multifunctional materials		D10. Safe operation of unmanned air vehicles in the national airspace	ASP/ AvSafe	E8c. Interfaces and procedures that support human operators in effective task and attention management
FA	A11. Robust and efficient multidisciplinary design tool								

Legend
FA
AvSafe
ASP
Not Planned Within ARMD
Multiple Program Support

Questions submitted by Representative Mark Udall

Q1. Please provide for the record a table of the Aeronautics budget and budget plan for the years FY 2004 through FY 2011 broken down by direct cost and full cost (identifying Corporate/Center overhead) elements and identify what is included in each element as well as any other assumptions.

A1.

Aeronautics Direct Cost and Total Full Cost Budget
FY 2007 President's Budget Request

10/23/06

$ in Millions	Estimated Prior		FY 2007 Budget Plan					
	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11
Aeronautics Full Cost Total	1057	962	893	724	732	732	723	723
Aeronautics Net Direct	788	685	594	452	451	450	439	439
Corporate/Center Overhead	269	277	299	272	281	282	284	284
Aviation Safety Program	183	183	148	102	102	116	120	120
Aeronautics Net Direct	136	131	95	62	60	73	75	75
Corporate/Center Overhead	47	52	53	40	42	43	45	45
Airspace Systems Program	232	149	174	120	124	105	91	89
Aeronautics Net Direct	173	106	123	76	81	66	52	50
Corporate/Center Overhead	59	43	51	44	43	39	39	39
Fundamental Aeronautics Program	642	630	571	447	449	453	453	453
Aeronautics Net Direct	479	448	376	271	265	266	266	266
Corporate/Center Overhead	163	182	195	176	184	187	187	187
Aeronautics Test Program	0	0	0	55	57	58	59	61
Aeronautics Net Direct	0	0	0	43	45	45	46	48
Corporate/Center Overhead	0	0	0	12	12	13	13	13

Direct Elements include:
- Mission Direct Labor
- Mission Direct Travel
- Mission Procurements
- Mission Demand Service Pools

Overhead Elements include:
- Corporate General and Administrative
- Center General and Administrative
- Construction of Facilities and Environmental Restoration
- Facilities and Information Technology

Note: Net Direct Budget does not include transfer of Engineering Technical Excellence to Center Overhead (i.e. Aero Net Direct in FY07 after Engineering TE transfer = $441M)
FY 2006 reflects the July Operating Plan

Q2. What fraction of the NASA Aeronautics budget is dedicated to research activities in support of the President's Vision for Space Exploration *(VSE) and other space activities?*

Q2a. Does that fraction stay constant over the next five years under your budget plan?

Q2b. How did you go about deciding how much of the Aeronautics budget should be used to support the VSE and other space activities?

A2a,2b. We do not typically parse our portfolio into "space-related" and "non-space-related" research. This is because a large portion of the research that we conduct in the Fundamental Aeronautics and Aviation Safety programs will benefit both the civilian aeronautics and space exploration communities. For example, advances in computational fluid dynamics modeling and lightweight high-temperature materials will be critical to successfully achieve reduced drag and improved engine performance on future air vehicles. But they will also be critical for the design of future space vehicles. Similarly, advances in integrated vehicle health management, flight deck technologies, and resilient aircraft control will be critical for the safety of the future fleet in the airspace, but such advances will also likely be of great value to future space vehicles.

The beginning and end of any trip to space takes place through the Earth's atmosphere. For this reason, research in Aeronautics has always been intimately linked to space exploration. About 20 percent of our research in both supersonics and hypersonics targets challenges associated with entry, descent, and landing that will ultimately benefit both robotic and human space exploration. However, the focus is not necessarily on either space or atmospheric flight, but rather on the generation of knowledge that can impact both. This focus of our supersonics and hypersonics research will remain roughly constant over the next five years.

Q3. In the concluding remarks of your written testimony, you state that your restructuring has resulted in "a total of ten research projects distributed across three programs." *Of those ten projects, how many are* new *projects, and how many are continuations of research activities underway prior to the restructuring? Please identify the new projects and how they differ from what was underway previously.*

A3.

Fundamental Aeronautics Program

The Fundamental Aeronautics program supports state-of-the-art research in tools and technologies that enable the design of vehicles that fly through any atmosphere at any speed. In particular, physics-based, multi-disciplinary design, analysis, and optimization (MDAO) tools developed in this program will make it possible to evaluate radically new vehicle designs and to assess, with known uncertainties, the potential impact of innovative technologies and concepts on a vehicle's overall performance.

Although the Fundamental Aeronautics Program is leveraging research results, tools, and expertise from the former Vehicle Systems Program, it represents a distinct shift in focus. Specifically, the Vehicle Systems Program often conducted research in support of point design solutions. For example, noise reduction research typically was conducted independently of emissions reduction research; airframe-related challenges were addressed independently of engine-related challenges, and so forth. Aircraft of the future will need to address multiple and usually conflicting design challenges such as noise reduction, emissions, fuel efficiency, and performance, and addressing any one independently of the others will lead to partial solutions at best, and at worst, solutions that are misleading or ineffective. The Fundamental Aeronautics program targets research that includes continued, long-term scientific study in areas such as physics, chemistry, materials, experimental techniques, and computational techniques that leads to a furthering of our understanding of the underlying principles that form the foundation of the core aeronautics disciplines, as well as that research that integrates the knowledge gained in these core areas to significantly enhance our capabilities, tools, and technologies at the disciplinary (e.g., aerodynamics, combustion, dynamics and control, acoustics) and multidisciplinary (e.g., engine design, airframe design) levels. This integrated approach to research represents a significant departure from the stove-piped approach of the past. We also note that our focus on cutting-edge research that targets fundamental aeronautical questions that we do not yet have answers for, particularly in supersonics and hypersonics, will benefit the future space exploration initiatives of the agency. We provide project-level specifics below.

Subsonic Fixed Wing Project
The project focus is to develop improved prediction methods and technologies for lower noise, lower emissions, and higher performance for subsonic aircraft. Higher performance includes energy efficiency and operability improvements that enable advanced airframe and engine systems. The pursuit of improvements in noise, emissions, and performance is fundamental to the development of environmentally acceptable and economically viable aircraft and because of this, portions of this research have been pursued in the past, and the results of this research will be leveraged as we go forward. However, as mentioned above, the synergistic approach to these challenges is a new focus of the SFW project.

Subsonic Rotary Wing Project
The Subsonic Rotary Wing project focuses its research on the technical barriers that constrain rotorcraft from reaching widespread use in civil aviation. These barriers include range, speed, payload capacity, fuel efficiency, and environmental acceptance (especially noise). Before the ARMD re-structuring, NASA had decided to eliminate its rotary wing research, a decision that would have resulted in an irreversible loss of critical core competencies needed to ensure that rotorcraft can play a significant and enabling role in the future airspace. This project thus represents a new effort relative to the program that existed before the restructuring.

Supersonics Project
The Supersonics project has two objectives. The first one is the elimination of the efficiency, environmental (emissions, noise, and sonic boom), and performance barriers to practical supersonic cruise in the Earth's atmosphere. Previous efforts in recent years tended to focus primarily on one challenge, that of sonic boom mitigation. Compared to more historical efforts, the current project has no intention of developing a supersonic commercial jet; rather, we will conduct cutting-edge research to advance our knowledge, tools, and capabilities so that companies in the private sector can leverage the research results in a manner that they decide makes sense from a market perspective. The second objective of the project is to address the critical issue of supersonic deceleration to enable safe, precision planetary entry, descent, and landing of human and large science missions in any atmosphere. This represents a new focus that had not been present in our previous supersonic research programs.

Hypersonics Project
All access to space, either suborbital or in Earth orbit, and all entry from space through any planetary atmosphere, requires hypersonic flight. In order to continue to advance our capabilities for flight in these regimes, improved understanding of hypersonic phenomena is needed. NASA had previously tackled research in the hypersonic regime but had been specifically interested in atmospheric sustained flight and had focused on point-design demonstrators. The new direction of the program will tackle all of the key fundamental research issues that are required to make hypersonic flight *and* re-entry feasible.

Aviation Safety Program

The Aviation Safety program builds upon the unique safety-related research capabilities of NASA to improve aircraft safety for current and future vehicles, and to overcome aircraft safety technological barriers that would otherwise constrain the full realization of NGATS. The program also provides long-term investment in research to support and sustain expert competency in critical core areas of aircraft safety. Previous aviation safety research initiatives focused largely on incremental research and on transitioning technologies that were already relatively well understood into deployable systems. In essence, both NASA and industry became development partners. As a result, there were no long-term fundamental research activities targeting the safety challenges of the future. It also meant that typically only certain companies were able to use the technologies that were developed, and that NASA, as a development partner, became a *de facto* partner with those particular companies in their certification issues with the FAA. Our new approach targets pre-competitive, long-term cutting-edge research and provides all the results of our aviation safety research to all of industry, as well as to the FAA and all other government agencies that have interest in our technical investigations. As we focus our research in areas that are appropriate to NASA's unique capabilities, this also means that work that is better left to other government agencies is no longer the focus of our research investigations. For example, we eliminated elements of our previous portfolio that were duplicative of research that belonged to the Department of Homeland Security (DHS). Details of the projects within this program follow.

Integrated Vehicle Health Management (IVHM): Aircraft manufacturers and operators are continually looking for ways to improve vehicle safety and service life while decreasing service cost. Advances in digital technologies have stimulated this trend through greater integration and automation of aircraft systems resulting in greatly improved system performance and reliability. Potential benefits to aircraft safety include on-board systems capable of self-detecting and self-correcting anomalies that could otherwise go unattended until a critical failure occurs. However, there are still significant technical barriers to the full implementation of highly integrated and complex vehicle health management concepts. State-of-the-art highly integrated systems do not inherently ensure that a minor malfunction or flaw will not propagate into critical software or a hardware function and jeopardize the safety of the entire vehicle. Research is needed to address current barriers and to exploit the full potential of integrated vehicle health management technologies. The outcome could possibly revolutionize the maintenance and utilization considerations of future aircraft vehicles. In addition to aircraft applications, these technologies will enable advanced self-healing systems that will likely be useful to future space exploration vehicles. The IVHM project is a new project. We note that its creation is well-aligned with the NRC Decadal Study recommendations, which included intelligent and adaptive systems as a major theme.

Aircraft Aging and Durability (AAD): Over the past decade, NASA in collaboration with the FAA and DOD has provided vital advances in material and structural sciences and technologies that have addressed many of the historical concerns and challenges associated with aging aircraft. However, the need to extend vehicle life and the growth in the use of composite structures and materials has caused NASA to recognize the need to augment its research in the area of advanced aging sciences. The research and technologies to be pursued within the AAD project will decrease the susceptibility of current and next generation aircraft and on-board systems to premature deterioration, thus greatly improving vehicle safety. Such research will also likely be applicable to future space exploration vehicles. The AAD project is a new project.

The Integrated Intelligent Flight Deck (IIFD) and *Integrated Resilient Aircraft Control (IRAC) projects* are not considered new projects, because they build upon previous research activities under the old program. With the focus of our

Aviation Safety research in areas appropriate to NASA's unique capabilities, FY 2006 became a transition year for the IIFD project and it now focuses on fundamental flight deck technologies of benefit to the entire aeronautics community. The scope of the IIFD project now includes the development of crew-vehicle interface technologies to reduce the risk of pilot error, the development of monitoring technologies to enable detection of unsafe behaviors, the development of fail-safe methods for changing the roles of flight crew and automation in the presence of detected disability states, and the development of a comprehensive surveillance system design that enables robust detection of external hazards with sufficient time-to-alarm for safe maneuvering to avoid hazards.

NASA will no longer fund efforts that belong in the research portfolio of the DHS. To avoid duplicating research activities that the DHS sponsors as part of its mission, NASA will redirect its aeronautics resources to those areas that NASA is uniquely suited to address. That said, the goal of the IRAC project is to pursue methodologies to enable an aircraft to automatically detect, mitigate, and safely recover from an off-nominal condition that could lead to a loss of control, and such a capability will have applications that include security-related issues (e.g., the ability to respond to critical upsets would include man-made as well as naturally occurring events). NASA will continue to coordinate with the DHS and other organizations as appropriate to ensure the efficient and effective transfer of potential new breakthrough technologies.

Airspace Systems Program

The Airspace Systems Program (ASP) currently comprises two new projects: the NGATS ATM–Airspace project and the NGATS ATM–Airportal project. Both projects contain elements of the former ASP but have been structured to ensure closer relevance to the NGATS vision. In pursuing the goal of a transformed national airspace system by 2025, NASA's ASP is focused on the longer-term, cutting-edge research necessary to create the NAS capable of supporting the tremendous throughput increases projected by the JPDO. To accomplish this, incremental research that leads to evolutionary enhancements has been set aside in favor of research that will enable revolutionary advances. Carry-over project elements include advanced traffic flow management, surface traffic management, and airspace modeling and simulation. NASA's project in small aircraft transportation systems (SATS) was successfully completed in FY 2006, and its research elements will be further matured as the restructured ASP seeks to answer the fundamental question as to the most effective allocation of functions between ground operations and flight deck operations (i.e., distributed versus centralized control). Human factors research remains a critical element of ASP, but in contrast to the previous program, it will be conducted as an integrated part of the advanced concept development research, rather than as an isolated project. Specifically, human factors research will tackle the fundamental question regarding the degree to which automation can be effectively and safely employed within the NAS.

New project technical thrust areas have been established to best respond to the anticipated needs of NGATS. Although they are new areas, the proposed work builds on well-established technical competencies. These include:

- Four-dimensional trajectory-based operations
- Performance-based operations
- Dynamic airspace configurations
- Super-density operations
- Coordinated arrival/departure operations management
- Airportal transition and integration management

All of these research thrust efforts will be integrated and coordinated across both projects within ASP. The essential goal of the program is to provide air transportation solutions that span the complete flight path from the departure gate to the arrival gate. This will only be possible through integration of the research in both the airspace and airportal domains.

ASP is no longer conducting research in communications, navigation, and surveillance (CNS) and UAVs in the NAS, given that other federal agencies have substantial overlapping efforts in those areas.

Q4. With respect to X-Vehicles,

Q4a. How many X-vehicle projects does NASA currently have underway? How many of those are new, and how many were already underway prior to the restructuring?

A4a. NASA is currently a participant in both the X–51 and X–48B projects. The X–51 project was officially set up in September 2005 and had its roots in the Air Force's Scramjet Engine Demonstrator program. The X–51 project is leveraging research results and expertise from NASA's X–43A project, and NASA has provided both expertise and facilities in support of it. Before the restructuring, NASA had decided to cease hypersonics research in FY 2005. The restructuring brought a renewed commitment to hypersonics as well as a desire to partner with the DOD when possible to avoid duplication of effort. Hence, at the beginning of the restructuring last fall, NASA renewed its commitment to the Nation's pursuit of cutting-edge research in hypersonics by joining the Air Force and Defense Advanced Research Projects Agency (DARPA) in the X–51 project.

The X–48B Blended Wing Body project represents a continuation of an existing effort. However, with the new focus on pre-competitive fundamental research, the X–48B project will now concentrate on leveraging what this non-traditional platform has to offer in terms of advancing our knowledge and capabilities in a variety of areas including acoustics, guidance and control, aerodynamics, and novel vehicle control actuators and strategies.

In addition to these X-projects, there are a number of other flight experiments currently being pursued by NASA (several in collaboration with other agencies) that do not have X-vehicle designations. Examples include the Hypersonic Boundary Layer Transition (HyBoLT) and Sub-Orbital Aerodynamic Re-entry Experiments (SOAREX) flight experiments, the Phoenix missile testbed, the Fundamental RE-Search from Hypersonic Flight eXperimentation (Fresh-FX) sounding rocket payload, and the DARPA Oblique Flying Wing and Falcon programs. The HyBoLT, SOAREX, and Phoenix programs are NASA-led and were started as a result of ARMD's restructuring.

Q4b. Which of these X-vehicle projects are primarily to meet civil aviation needs, as opposed to supporting military or space exploration needs?

A4b. As with most X-vehicles, the projects are designed to pursue the unknown and advance the state of knowledge in aeronautics. Historically, when such projects have involved both NASA and the DOD, they have produced new knowledge and data that have ultimately benefited both the civilian and military communities. The same is true now. The X–48B Blended Wing Body aircraft is a good example of an advanced aircraft concept that has potential civilian and military applications. The DARPA Oblique Flying Wing and Falcon programs have primarily military applications, but the knowledge gained from them has important applications for civilian purposes. The HyBoLT, SOAREX and Phoenix projects have been developed primarily for civilian applications but the data gathered will likely be useful to our military partners. This "dual use" of technology explains why NASA and the DOD have enjoyed such success with X-vehicle research.

Q4c. Do you have any other X-vehicle projects planned and budgeted for *over the next five years? If so, what are they?*

A4c. We have budgeted for the projects mentioned in answer 4a above.

Q5a. In your testimony, you discuss why you believe NASA should not support technology demonstrations of point designs. On the other hand you point to past successes of what you term flight experiments, such as the "X-series" aircraft.

So should we conclude that you believe it is appropriate for NASA to fund flight experiments that would serve to explore the feasibility and range of flight conditions, say, over which a particular technology may be effective for ultimate incorporation into the design of a specific flight vehicle?

A5a. We will conduct flight experiments to advance our knowledge, which could very well include the kind of example cited in your question, assuming the technology represented a potentially significant advance in state-of-the-art, and not an incremental advancement.

Q5b. For example, would you find it appropriate for NASA to support a flight experiment involving the testing of a flexible, controllable wing structure that could deform for different flight conditions, eliminating the need for movable control surfaces, such as flaps?

A5b. Through a reimbursable agreement, NASA is currently the technical and contract agent for the DARPA Morphing Aircraft Structures (MAS) Program. The MAS program is pursuing the ability to design and operate aeronautical structures capable of substantial wing area, span, and sweep changes for in-flight performance optimization that can move reliably from one shape to another. In addition, the program intends to develop active wing structures that change shape to provide a wide range of aerodynamic performance and flight control not possible with conventional wings. NASA's role includes providing leadership and technical expertise in several areas (flight dynamics, controls, structures, aerodynamics, aeroelasticity, systems engineering and integration, and flight and wind-tunnel testing) that are required to enhance our understanding of the physical phenomena involved. In collaboration with Lockheed Martin Aeronautics and NextGen Aeronautics, NASA will conduct wind-tunnel tests and Airworthiness and Safety Reviews for the program.

Q5c. Does your five-year budget support such types of flight experiments? If so, how much are you including in your budget for such activities in each of the years FY 2007 through FY 2011?

A5c. We do not currently have plans for additional active aeroelastic flight experiments, apart from the reimbursable work cited in answer 5b above. We do have a number of other flight experiments planned as described in our previous answers above.

Q6. Based on your testimony, you indicate that with the exception of the $50 million NRA awards, all of the aeronautics research funded by NASA will be done by NASA employees and their Center-based support contractors. Other than competing with universities for the NRA awards, industry's role will be confined to working with NASA on an unfunded basis through Space Act agreements. As I understand it, NASA historically had split its research dollars roughly 50–50 between external and in-house research. Why have you decided to pull so much of the aeronautics research funding back into the agency?

A6. NASA respectfully disagrees with the 50/50 statistic referenced in this question, and we have attached data from the past five years supporting this conclusion. Our data shows that the historical percentage of out-of-house funding versus the appropriated total (which includes Congressionally-directed projects and other direction from Congress), is closer to 20 percent, based on a definition of "out-of-house" that excludes on-site contractors, hardware and software procurements for laboratory, tunnel, simulator, and flight tests, and NASA Headquarters procurements for supporting commitments to studies and the JPDO.

The out-of-house funding versus the President's request without Congressionally-directed projects (which is what would provide the true apples-to-apples comparison for FY 2007) ranges from nine to 14 percent. If you can provide the source of the data showing the 50/50 split, NASA would be happy to evaluate it and try to explain the discrepancy.

Aeronautics Budget (Out-of-House vs In-House) 10/18/06

($,M)

	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11
Appropriated Amount (FY00-FY06):	997	1,004	1,057	962	893	724	732	732	723	723
President's Budget Request (est FC):	934	986	959	919	852	724	732	732	723	723
Out of House Effort	226	195	181	174	176	51	51	51	51	51
Earmarks	*99*	*77*	*87*	*88*	*96*					
Grants/Cooperative Agreements and Out-of-House Contracts	*127*	*118*	*94*	*86*	*80*	*51*	*51*	*51*	*51*	*51*
Out-of-House: % of Appropriated Total including earmarks	23%	19%	17%	18%	20%	7%	7%	7%	7%	7%
Out-of-House: % of President's Budget Request w/o earmarks and approps	14%	12%	10%	9%	9%	7%	7%	7%	7%	7%

Assumptions: Out-of-House contracts includes those supporting Rotorcraft (FY02 only); ERAST (FY02 and FY03 only); X43A (FY02-FY04); UEET (ends in FY05); orderly phase-out of projects/$30M in FY06 only)

Note: FY02 and FY03 are estimated full cost budgets which include in addition to the R&D budget: Civil Servant salaries, overhead, travel, and Construction of Facilities and Environmental Restoration at the Research Centers.

NASA's aeronautics research program has always had a strong in-house component of world-class researchers. This is essential in order to ensure that the research that we conduct benefits the community broadly rather than targeting one or two specific interests. It is also essential in our role as a source of independent technical advice to our government partners in the FAA, JPDO, and the DOD. We will not abdicate our responsibility to provide the intellectual stewardship of the core competencies of aeronautics for the Nation, and this requires that we sustain our in-house, world-class expertise.

Q7a. Given the importance your testimony attaches to the interagency effort to develop the Next Generation Air Transportation System [NGATS], it doesn't appear on the surface to make much sense for NASA to be cutting its funding for Airspace Systems research from $120 million in FY 2007 (which in itself represents a $54 million decrease *from the 2006 level) to a level of just $90 million in FY 2011. Moreover, given the impact of the decrease in purchasing power due to inflation over the next five years, the rationale for such a cut is unclear.*

What specific guidance, if any, did you receive from the interagency Joint Planning and Development Office (JPDO)—the organization charged with developing the NGATS—that gave you the basis for cutting NASA's Airspace Systems budget by that amount over the next five years? Please provide that guidance for the record.

A7a. The Airspace Systems Program (ASP) research portfolio has been developed in substantial collaboration with JPDO leadership. JPDO senior leaders contributed to reviews and assessments of ASP early program planning material and served as key participants in the review of the project proposals submitted i11 the spring of 2006. As part of those reviews, the JPDO representatives stated that the proposed program content was relevant and aligned with the NGATS vision. ASP has continued to refine its technical roadmaps and resource plans through comparison to the recently published JPDO concept of operations. However, specific adherence to an NGATS schedule cannot be assured until the Enterprise Architecture, the Operational Improvement roadmaps, and the Integrated Capability Work Plans are developed and agreed to by the JPDO members. These activities are scheduled to culminate during FY 2007. ASP will continue to pursue its research agenda and will revisit its program objectives as more planning guidance from the JPDO becomes available.

We note that the JPDO, as a planning and development organization, does not have the authority to direct the budgets of any of its five member agencies, so there is no specific JPDO budgetary guidance to submit for the record.

Q7b. What specific guidance, if any, did you receive from the Office of Management and Budget regarding cutting the Airspace Systems budget by that amount over the next five years? Please provide that guidance for the record.

A7b. The FY 2007 President's Budget Request was approved by the Office of Management and Budget to meet the needs of NASA's refocused aeronautics research priorities. This allocation has enabled NASA to develop an aeronautics research portfolio that achieves the following three core principles: 1) we will dedicate ourselves to the mastery and intellectual stewardship of the core competencies of aeronautics for the Nation in all flight regimes; 2) we will focus our research in areas that are appropriate to NASA's unique capabilities; and, 3) we will directly address the fundamental research needs of the NGATS while working closely with our agency partners in the JPDO.

Q7c. If you didn't receive any specific guidance from the JPDO, please provide for the record the specific analyses that were the basis for your decision to cut the Airspace Systems budget by that amount over the next five years.

A7c. NASA's research portfolio has been constructed according to the following three core principles: 1) we will dedicate ourselves to the mastery and intellectual stewardship of the core competencies of aeronautics for the Nation in all flight regimes; 2) we will focus our research in areas that are appropriate to NASA's unique capabilities; and 3) we will directly address the fundamental research needs of the NGATS while working closely with our agency partners in the JPDO. As such, we have prioritized our research based on these principles.

Our commitment first and foremost must be to provide the mastery and intellectual stewardship of the core competencies of aeronautics for the Nation. This includes core competencies relevant to ATM research, of course, but it also includes a large number of other critical research areas that are addressed in our Fundamental Aeronautics and Aviation Safety Programs. Our research must focus on areas appropriate to NASA, which means that we are phasing out work in the Airspace Systems program that is near-term, incremental research as well as prototyping and operational development. Finally, our commitment to conducting the fundamental research needs of the NGATS necessitates a balanced research portfolio that draws upon our NASA-unique capabilities to address ATM, environmental, efficiency, and safety-related research challenges, all of which must be worked in order for the NGATS vision to be realized.

The four-step process described in the written testimony explains how the research plans for all of the programs, including the Airspace Systems Program, were developed. The detailed technical proposals that resulted from that process were assessed for the quality of their technical, management, resource, and partnership plans, and members of the JPDO, the FAA, and NOAA participated in that review process.

Finally, we would like to emphasize that NGATS is not our only key commitment. While it is a commitment that was highlighted in the written testimony, we take our commitment to provide cutting-edge research for the benefit of the broad aeronautics community seriously. This community includes the JPDO but is by no means limited to it. Our research provides critical knowledge, tools, concepts, technologies, and capabilities for our partners in the private sector (including the commercial sector and academia), the DOD, and our colleagues within NASA's space exploration community, and we cannot focus our attention on any one of them exclusively.

Q8. At a recent congressional hearing on the interagency Joint Planning and Development Office [JPDO] and its effort to develop the next generation air transportation system [NGATS], the GAO witness testified that:

> ". . .many experts told us that NASA's new focus on fundamental research creates a gap in the [NGATS] technology development continuum. . .REDAC [the FAA's R&D Advisory Committee] further estimated that establishing the necessary infrastructure in FAA could delay the implementation of NGATS by five years."

What specifically have you done to ensure that your restructuring will not adversely impact the Nation's ability to field the next generation air transportation system as soon as possible?

A8. NASA's return to fundamental aeronautics research is precisely what is required if we as a nation are serious about the NGATS vision. The vision is not an incremental advance on the existing system; it represents a true paradigm-shift and it requires a commitment to long-term, cutting-edge research. Such a commitment is precisely what NASA's new program is offering. Our return to fundamental, innovative research will increase the probability of development of the revolutionary technologies that will be required for the successful implementation of NGATS and will broaden the advanced technology development options.

The Airspace Systems Program (ASP) research portfolio has been developed with substantial collaboration with JPDO leadership. JPDO senior leaders contributed to reviews and assessments of ASP early program planning material and served as key participants in the review of the project proposals submitted in the spring of 2006. As part of those reviews, the JPDO representatives expressed that the proposed program content was relevant and aligned to the NGATS vision. ASP has continued to refine its technical roadmaps and resource plans through comparison to the recently published JPDO concept of operations.

It is important to note that the Enterprise Architecture, the Operational Improvement roadmaps, and the Integrated Capability Work Plans are still being developed. These activities are planned to be settled during FY 2007. If these documents identify gaps in technology development or other areas, NASA and its JPDO partners will work together to address those gaps. In the meantime, ASP will continue to pursue its research agenda and will revisit its program objectives as more planning guidance from the JPDO becomes available.

Finally, NASA is one of five member agencies participating in the JPDO, and our role is to provide the fundamental research that will enable the NGATS vision. We are not responsible for the implementation of NGATS. That responsibility lies with the Federal Aviation Administration.

Q9. Relative to the level of technology development NASA would support for a particular technology, do you differentiate between technologies that are relevant to commercial applications and technologies that are required to meet federal agency needs? I have in mind NASA's support for the JPDO and its goals for national airspace modernization.

A9. NASA will not conduct near-term, incremental research, nor will we develop prototypes or operational systems. With regard to the fundamental research that we conduct in support of the NGATS, the algorithms, concepts, tools, and technologies that we develop will be broadly disseminated, and through our collaborative research partnerships with the other member agencies of the JPDO as well as the private sector, will be easily accessible to all stakeholders. We note that, to the extent that the future system is expected to be one that will employ substantial collaborative decision making as it seeks to optimize operations in the NAS, research outcomes that support air navigation service providers (i.e., government) and aircraft operators (i.e., airlines, private pilots, etc.) will be largely indistinguishable.

Q9a. Given that NASA is the prime provider of R&D for the FAA, what is NASA's responsibility for moving air traffic management technologies up the Technology Readiness Level scale for the JPDO so that the FAA will be able to pick it up and use it in the airspace system with the least delay?

A9a. The FAA is only one member of the aeronautics community whose needs guide NASA's research; our research must benefit the broad aeronautics community, which includes our government partners in the FAA and the DOD, our partners in space exploration, and our partners in industry and academia. We will conduct experiments on the ground and in the air that explore the feasibility of advanced concepts and technologies, but we will not prototype and we will not develop operational systems, including operational software. The FAA is responsible for implementation of the advanced tools, concepts, and technologies developed at NASA that are relevant to NGATS.

NASA's greatest contributions to the aeronautics community result from its ability to conduct high-quality, cutting-edge research that yields tools, concepts, and technologies that build technical capability leading to multiple potential solutions to the challenges of the future. NASA creates and disseminates knowledge with the widest practical applicability, and will not prototype technologies that lead to point-design solutions for today. The solutions needed for the NAS of 2025 require transformational research and experimentation that NASA is uniquely prepared to provide.

Q9b. What is the farthest you envision NASA taking Air Traffic Management technology development in support of the JPDO and NGATS? Do all of the members of the JPDO agree with you on that? And have you budgeted for such a level of technology development?

A9b. NASA will test the feasibility of advanced ATM concepts, algorithms, and technologies by means of systems-level numerical simulations. We will not prototype, and we will not develop operational systems, including operational software. While we cannot speak for every individual member of the JPDO, both the JPDO Director and the FAA Administrator have told us they understand NASA's position and have not indicated that this will lead to insurmountable challenges for NGATS implementation. NASA's budget supports the Agency's experimental plans.

Q10. In your testimony, you state that you are spending some fraction of $130 million on "JPDO procurement funds." *How much are you spending on JPDO procurements, and what specifically are you spending the money on?*

A10. NASA contributes $6 million to JPDO for its procurement needs, particularly in its Evaluation and Analysis Division. It spends the money on a variety of contractors who specialize in systems analysis.

Q11. In your testimony, you discuss your outreach to the aeronautics community. However, based on the charts you provided to Committee staff, all but a handful of your meetings with aeronautics stakeholders have taken place after *you announced your restructured aeronautics program in January of this year. What specific input did you seek from industry or academia* prior *to announcing your restructured R&D roadmaps at the AIAA conference in January 2006, and what, if any, was your mechanism for getting that input?*

A11. In January 2006, NASA announced plans for the upcoming restructuring. We did not present a restructured program, as we were just beginning the process. We provided preliminary roadmaps that evolved with industry, academic, non-profit, and other government agency participation over the ensuing months into roadmaps that in many cases now look quite different from their starting point.

NASA's researchers are renowned for their expertise in the core competencies of aeronautics, and they have long enjoyed professional relationships with people from many different companies. Given this expertise and experience, my senior staff and I felt that it was appropriate to ask them to formulate, through a series of workshops, an intelligent and independent starting point for the future direction of our aeronautics research. It was important that this starting point incorporate their knowledge based on years of interactions with the private sector, but without any bias or influence from particular companies. The preliminary roadmaps that resulted from these workshops were vetted with senior subject matter experts in the DOD, the FAA, and the JPDO before being presented publicly in January 2006.

NASA believes that all companies, regardless of size or location, must have equal access to information and opportunities for collaboration with us. This was the motivation behind the four-step process that was described in detail in the written testimony submitted at the hearing on September 26, 2006. We received over 230 responses to our Request for Information from over 100 different organizations throughout the country. Many of these organizations had not provided input into NASA's aeronautics program in the past. This input was carefully considered in the development of the research plans we currently have in place. Thus, we firmly believe that our approach has resulted in a process that includes all and excludes none who are interested in participating. We believe it is our duty to the taxpayer to conduct research that benefits the community broadly and to ensure that access to information and opportunities for collaboration with NASA are provided fairly and equally to all in the Nation's aeronautics community.

In addition, our research portfolio aligns very well with the recommendations of the NRC Decadal Survey, which included participation from many members of the private sector. Forty-seven of the 51 technical challenges recommended by the NRC are currently present in our restructured portfolio. This is a strong affirmation that our four-step process resulted in research plans that are focusing on the proper challenges across our entire portfolio.

With regard to your question about what external input was used before January 2006, there were several sources. First, before I became the Associate Administrator, I was the Senior Advisor to the NASA Administrator in Aeronautics, and in that position, I met with the members of the Super10 alliance (Boeing, Cessna, Gulfstream, Lockheed Martin, Northrop Grumman, Raytheon, General Electric, Pratt & Whitney, Rolls-Royce's Allison Advanced Development Unit, and NetJets), with a senior member of the Aeronautics Research Advisory Committee before it was disbanded as part of the Agency's restructuring of its advisory councils, with the leader of the RAND wind tunnel study, and with the Aeronautics and Space Engineering Board (ASEB). I also made it a point to meet with the FAA Administrator, the FAA's Associate Administrator for Safety, the Director of the JPDO, the Chief Scientist of the Air Force, and the Tactical Technology Office Director at DARPA.

The following reports also provided important material that influenced the reshaping process:

- *Final Report of the Commission on the Future of the U.S. Aerospace Industry,* Aerospace Commission, 2002
- *Aeronautics Research and Technology for 2050: Assessing Visions and Goals,* National Research Council (NRC), 2002
- *Securing the Future of U.S. Air Transportation: A System in Peril,* National Research Council (NRC), 2003
- *Wind Tunnel and Propulsion Test Facilities: An Assessment of NASA's Capabilities to Serve National Needs,* RAND Corporation, 2002/2003
- *Review of NASA's Aerospace Technology Enterprise: An Assessment of NASA's Aeronautics Technology Programs,* National Research Council, 2004
- *Responding to the Call: Aviation Plan for American Leadership,* National Institute of Aerospace (NIA), 2005.

We note that the NIA report was particularly comprehensive and represented a wide range of participation from the community. Many have correctly observed that this report had a strong influence on our restructuring. The report covered a breadth of research areas in all flight regimes (there was a chapter for subsonics, rotorcraft, supersonics, and hypersonics) as well as aviation safety and airspace systems, it advocated for long-term, cutting-edge research, and it attempted to provide an integrated roadmap for each of the areas with links from foundational research to systems-level capabilities.

After I became the Associate Administrator, but before January 2006, I met with the AIA, ASA, ATK, UNITE (the UAV alliance), Flight Safety Technologies, and Northrop Grumman. Then as now, my Deputy and I have an open-door policy about meeting with those in the aeronautics community.

Questions submitted by Representative Michael M. Honda

Q1. When NASA provided its input to the President's budget last fall, NASA had not yet received input either from its in-house Aeronautics technical experts at Langley, Glenn, Ames, and Dryden through your workshop process or from industry stakeholders. What were the data and analyses used to justify NASA's dramatic cut in the Aeronautics top-line from the $912 million initially appro-

priated in FY 2006 to the $724.4 million in the President's proposed FY 2007 budget? What were the analyses used to determine the program and center breakdown of the proposed FY 2007 Aeronautic budget? Please provide the Committee with the data and analyses used to drive the approximately 30 percent cuts in the Aviation Safety and Air Traffic Management programs.

A1. The FY 2007 President's Budget Request for aeronautics meets the needs of NASA's refocused aeronautics research priorities. This allocation has enabled NASA to develop a balanced aeronautics research portfolio that achieves the following three core principles: 1) we will dedicate ourselves to the mastery and intellectual stewardship of the core competencies of aeronautics for the Nation in all flight regimes; 2) we will focus our research in areas that are appropriate to NASA's unique capabilities; and, 3) we will directly address the fundamental research needs of the NGATS while working closely with our agency partners in the JPDO. The four-step process described in the written testimony explains how resources were allocated to the four research centers as well as to out-of-house procurement, including the NRAs. The technical research plans that resulted from the peer-review process are quite long and detailed but are available on-line at our web site *(www.aeronautics.nasa.gov).* The results of the NRA source selections will be made available when awards are made in November 2006.

The $54 million (~30 percent) decline from FY 2006 to FY 2007 in the Airspace Systems program is due to the planned completion and/or phase-out of certain projects. The Small Aircraft Transportation Systems (SATS) project was completed in early FY 2006 after a successful demonstration in June 2005. The Virtual Airspace Modeling and Simulation Project and Wake Vortex Alleviation efforts are ramping down during FY 2007 as previously planned. The Unmanned Aerial Vehicles in the NAS Project, which was created to formulate policy recommendations to the FAA for their operational control of UAVs, has provided a final NASA report on the findings to FAA as part of the FY 2006 phase-out, and in accordance with direction provided in the Conference Report (House Report 109–272) accompanying H.R. 2862, the FY 2006 Science, State, Justice and Commerce Related Agencies Appropriations bill. The Space-Based Technologies Project has also been phased out, because it was duplicative of research being conducted by the DOD. The sum total of these FY 2006 budgets was $46 million. In addition, $8 million of site-specific, Congressionally-directed projects are not included in the FY 2007 Budget Request.

In Aviation Safety, the $46 million (~30 percent) decline is a result of the planned completion and phase out of several activities. The Aviation Security research initiative completed a planned orderly phase out in early FY 2006. Other activities that were completed in FY 2006 include incremental research in turbulence detection technologies, and a Safety Program assessment study. Work in an Information Sharing Initiative (ISI) was also scheduled for completion in FY 2006. However, in response to feedback from the FAA and Industry a portion of the ISI activity is being reinstituted to focus on development of advanced tools for data mining of disparate sources of information. In addition, $7 million of Congressionally-directed projects are not included in the FY 2007 Budget Request.

Q2. The more than 20 percent overall cut in NASA's aeronautics program is one of the major causes of the workforce turmoil at the Agency. Over the last two years, through accelerated attrition, (through buyout incentives and pressures) as well as the assignment of formerly-aeronautics engineers to cover ESMD work packages, NASA's Aeronautics program has lost a measurable portion of its intellectual capabilities. What analysis have you performed to evaluate the impact of this loss of human capital, and what hiring strategy have your formulated to assure that over the next five years NASA Aeronautics does not loose the core competencies and workforce it will need to meet the long-term goals of your programs?

A2. While ARMD does not set the hiring strategies for the Agency, we believe that our pursuit of the cutting edge coupled with our full and open NRA process will help to replenish and enhance critical areas of aeronautics research and will help ensure that NASA does not lose core competencies and the workforce needed to meet the long-term goals of the programs.

ARMD also is taking an active role in developing a workforce that will help retain the United States' leadership in aeronautics. ARMD sponsored a workshop on June 1, 2006, to explore what can be done to improve the technical capabilities of the future workforce to meet the needs of both NASA and the aerospace industry. Workshop participants from government, industry, academia, and professional and industry organizations discussed the future of higher education, and what can be done to better define and fill any gaps in the current education system that might prevent students from pursuing aerospace and aerospace-related careers. Outcomes of the workshop included a number of ideas and concepts, both near-term and long-term, about how we can all work together to improve the size and capability of the future technical workforce.

Following the workshop, ARMD redefined a number of its educational activities to better align with ongoing activities within universities, industry, and outside organizations. ARMD is partnering with these outside organizations by providing technical expertise to help train and educate the future aerospace workforce. These partnering activities include a series of case studies or lessons-learned monographs on aeronautical topics; expansion of its "Beginner's Guide to Aeronautics" Web-based learning to include an updated module on the hypersonic regime; a series of university texts and supplemental materials to fill gaps in the current educational background of university students; support of design competitions that provide university students with hands-on experience in the design and testing of aerospace systems; and better methods for communicating NASA's educational and research opportunities to stakeholders.

It is also important to note that the fact that some aeronautics engineers are now working on Exploration Systems Mission Directorate (ESMD) projects, while others are splitting their time between ARMD and ESMD projects, and others yet find themselves supporting even more than two mission directorates, is a great result of the Agency's initiative to break down historical stovepipes across centers and across mission directorates. Such cross-fertilization of skills between aeronautics and space-related activities is a positive factor and will help ensure that knowledge flows freely between the directorates.

Q3. Your Aeronautics program concentrates on the development of products for the long-term (10–20 years out), while the FAA focuses on immediate needs. Many changes in vehicle mix and Air Traffic Control architecture are planned for an intermediate timeline. What specific R&D activities are addressing safety and efficiency during the mid-term, especially during the transition to the new National Airspace System and to the era of rapidly increasing vehicle heterogeneity?

A3. NASA aeronautics' long-term research focus requires us to anticipate mid-term goals and objectives in our research, both to measure overall progress, and to determine viable options for further pursuit. Additional appropriate milestones and metrics established at shorter intervals along the way will ensure that we continually evaluate progress and results.

For example, the research activities of the Airspace Systems Program (ASP) will include development of advanced system-level concepts as well as modeling and simulation tools to assess the performance of proposed advanced concepts. The goals of system flexibility and scalability are currently being built into our tools and simulations in order to anticipate and accommodate the uncertainties in demand, the mix of aircraft and avionic equipment in the fleet, as well as operational concepts and system architectures.

Leading up to the mid-term, our research tools and capabilities will be continually improved. This in turn enables the trades that will be essential to evaluate the performance of candidate "mid term" and "advanced" concepts. NASA's research to date has provided the state-of-the-art of such tools, which are currently used by the JPDO to make the trades and assess proposed concepts in order to define system requirements. Based on experience, we anticipate that our intermediate results will be directly relevant to the needs and advances in the National Airspace System.

As another example, the Integrated Intelligent Flight Deck (IIFD) project in the ASP will be developing technologies within the next five years to improve the pilot's situational awareness of the cockpit and external environment. This will enable the pilot to better adapt to changing workload and procedures as a result of new capabilities introduced into the NAS.

Q4. Most accidents can be traced, not to vehicle component failures, but rather to a series of operational and environmental occurrences that together result in an anomalous event. How does your Aeronautics program address system-level design and failure mitigation, i.e., the emergent impact of combining technological, human, and environmental factors? Given that human error and weather constitute two of the largest remaining risk factors in aviation safety, why has research and development in these key areas been de-emphasized in your Aviation Safety Program?

A4. Within the Aviation Safety Program, research involving Human-System Interactions and/or system level-safety is included across multiple projects. Additionally, it is a focused activity within the IIFD project, which has developed a 10-year roadmap for integrated multi-disciplinary research that captures the breadth of research needs for improved flight deck system safety. The research planning considers a flight deck system wherein one or more human operators are elements of this system. This acknowledges the fact that the act of safely directing a flight in current and future operational environments requires a complex system whose behavior will result from a strong coupling of physical processes, human behavior, accurate weather information, and computer-controlled systems. As a result, an overarching guideline is promoted in the research to apply an integrated holistic approach in order to bring about new system-level capabilities such as those envisioned by the NGATS while simultaneously improving safety.

Regarding weather-related research, NASA has already completed extensive research in hazardous weather detection and avoidance, much of which has already transferred into operational use. We will be building on this work in the IIFD project to develop technologies to help aircraft system designers and operators better integrate human performance, weather information, and new automation capabilities into the flight deck environment.

Q5. Currently, many more people die each year in U.S. General Aviation accidents than in commercial jets. To what extent have you consulted with the GA community on its R&D needs? How does your Aeronautics program address the impact of widely diverse GA aircraft (heritage, technically advanced, and very light jets) and Unmanned Aircraft operation in the National Airspace System of the future?

A5. Because of NASA's focus on fundamental, pre-competitive research that has broad applicability to a wide variety of air vehicles, rather than on research that targets point-design solutions, much of the research in both the Fundamental Aeronautics and Aviation Safety programs will benefit the GA community and Unmanned Aircraft Systems as well as large transport aircraft.

In January 2006, NASA issued a Request for Information (RFI) to solicit input from industry to include interest in collaborative non-reimbursable partnerships. The RFI was open to all vehicle classes to include the GA community. In the Aviation Safety Program, we received about 50 responses from industry organizations expressing an interest to collaborate in Aviation Safety research, including responses from a GA airframe manufacturer and numerous avionics suppliers for GA aircraft. We have already visited Gulfstream, and are in discussions with them for collaborative activities. Our upcoming travel plans include a trip to Raytheon and Cessna, and we have already met with several avionics companies.

We would also like to note that the SATS project had very close participation with the GA community and conducted a research agenda that addressed many of its needs. Elements of that project have been incorporated in the new program structure as the Airspace Systems Program plans to examine the questions of safely and efficiently providing automated self-separation from the flight deck and in allocating distributed and centralized air traffic control roles and responsibilities. These basic questions are the same ones that need be addressed as the Nation seeks to accommodate the varied business models for airspace operations that include a widely mixed fleet and unmanned autonomous aircraft.

Q6. Given NASA's unique role in the aviation industry as an "honest broker" respected by all stakeholders and given NASA's track record as the best source of operationally relevant research and applications, why has your Aeronautics program cut most operationally relevant research? Indeed, given the long lead time and high cost of integrating new technologies into advanced vehicles versus the near-term impact and low cost of safety interventions such as enhanced training and procedures, why is NASA cutting its R&D in these low-cost, high-payoff areas?

A6. NASA's role is to conduct the long-term, cutting-edge research for our partners in both the Government and private sector who will then develop the prototypes and operational systems appropriate to their missions. It is not NASA's role to conduct near-term incremental research nor is it our role to develop prototypes or operational systems. Furthermore, it is not our role to make recommendations regarding safety procedures. This responsibility belongs to the Federal Aviation Administration (FAA).

While we appreciate that people consider NASA to be an "honest broker," we think that this implication discredits the safety motives of both industry and other government agencies. It has been through their vigilance, with contributions from NASA, that our U.S. Air Transportation System is widely recognized as among the safest operations in the world. Given this evidence of vigilance, there are other capable organizations within the U.S. aviation community who can also act as honest brokers when it comes to safety. NASA must return to its unique role as a research entity that invests in long-term cutting-edge research that has a potentially high pay-off for the Nation, but which is too high risk for industry to pursue alone. NASA will continue to collaborate with industry and other government agencies to ensure that our research is relevant to the future needs of the broad community, and that the new capabilities, tools, and technologies that we develop can be transferred to the community as quickly and efficiently as possible. The FAA has the responsibility, capability, and the authority to ensure that the current and near-term air transportation system is as safe as possible.

Q7. How did you determine the priorities of your Aviation Safety program? Prior to sending the proposed FY 2007 budget to OMB last fall, what did you do to ascertain the critical needs of key aviation stakeholders—e.g., pilots, airlines, manufacturers, helicopter operators, GA operators, FAA, NTSB—before setting the R&D priorities and budget of the new Aviation Safety program?

A7. At the beginning of the first focused Safety Program in 1997, NASA sponsored a series of workshops with industry and government participants to identify and prioritize NASA's portfolio of safety research activities that would support the National Goal to reduce the fatal accident rate. In addition to NASA's own expertise, participation at the workshops included representatives from the Air Transport Association, the GA and Rotorcraft community, Boeing, the airlines, avionics suppliers, the FAA, and other government agencies. As the second phase of the Safety program was being planned in 2004, NASA built upon this knowledge base and conducted another workshop with industry and government participation to refine and prioritize NASA's portfolio of proposed Safety research activities. Even though the current planning reflects a shift to more fundamental research, previous findings of the safety workshops influenced the portfolio of activities in each of the project areas. We also continue to be directly involved with the Commercial Aviation Safety Team (CAST), which is a collaboration of government and industry organizations from the commercial transport aviation community that identifies, implements, and tracks new interventions intended to improve aviation safety. The *2007 CAST Plan Implementation Values* report was a valuable resource in the development of the research plans for IVHM, IRAC, and IIFD. Furthermore, in January 2006 NASA issued a Request for Information (RFI) to solicit input from industry for collaborative non-reimbursable partnerships in aviation safety research. We received about 50 responses from a variety of industry organizations expressing an interest to collaborate.

Q8. NASA Aeronautics R&D can play a significant role in supporting U.S. economic competitiveness. By what means have you assessed the synergy of your proposed Aeronautics fundamental research portfolio with U.S. industry's development pipeline?

A8. NASA's research should not be aligned with industry's current development pipeline, but rather, the future system-level challenges that industry faces. In order to ensure that our research plans address those key challenges in a pre-competitive manner, so as to be useful to all of industry, we employed the Request for Information (RFI) process as described in the written testimony, and we incorporated the feedback from those RFIs into the proposal development. We are also reaching out to the strategic thinkers in industry by traveling to companies across the country to discuss opportunities for collaboration and to ensure that the lines of communication remain open. We have also begun a series of informal meetings with the aeronautics community that we intend to hold on a regular basis in order to maintain open lines of communication. It is anticipated that aeronautics leaders from industry, academia, industry associations, and non-profit associations will make up the pool of participants for the meetings, with the particular meeting topics determining the make-up of the meeting attendees. These meetings are not intended to generate definitive or consensus recommendations, but to provide participants with a forum to express their various individual points of view as experts in their field. ARMD's research programs are also using Industry Days as an effective means to reach out to our industry stakeholders. Industry Days are a useful means for industry participants to discuss the particulars of potential pre-competitive research partnerships appropriate for work under Space Act Agreements.

Finally, we would point out that our research portfolio aligns very well with the recommendations of the NRC Decadal Survey, which focused its attention on research challenges in civil aeronautics, and which was conducted completely independently of our own restructuring. Forty-seven of the 51 technical challenges recommended by the NRC are currently present in our restructured portfolio (see attached Cross-walk matrix). We believe this is a strong affirmation that we are focusing our efforts on the proper research areas across our entire portfolio.

Q9. In contrast to scheduled airline operations, large segments of the rotorcraft community such as emergency medical service and off-shore oil support helicopters are experiencing increasing accident rates and risk exposure. What is your Aeronautics program doing to improve the near-term operational safety of these important categories of aviation, independent of long-term technology development efforts?

A9. As with the fixed wing community, NASA will continue to collaborate with industry and other government agencies to ensure its research is relevant to the future needs of the rotorcraft community, and that the result of its research can be transferred to the user community as quickly and efficiently as possible. Representatives from the rotorcraft industry have visited NASA and we have been to their facilities to discuss potential areas of collaboration. NASA is planning to participate in the International Helicopter Safety Team, which is an entity similar to the Commercial Aviation Safety Team that is made up of industry and government organizations that have teamed together to identify and address safety concerns.

Questions submitted by Representative Brad Miller

Q1. Please provide for the record your response to the question of whether it is correct that NASA Ames Center has lost 15 percent of its civil service human factors experts and close to 70 percent of its contractor and academic human factors technical support since the beginning of FY 2005. If it is incorrect, please provide the correct numbers. Do you agree that such losses are a problem, and if so, what are you doing to replenish NASA's human factors capabilities?

A1. The reformulation of NASA's Aeronautics program has built integrated, multidisciplinary research projects in place of isolated, stand-alone activities that had little connectivity to higher-level objectives. As a result of this new focus, the appropriate skill mix to conduct the research changed. Human factors research continues to be a critical component of NASA's Aeronautics program, but now it is directly connected to the broader goals of the program as a whole. Implementing this reformulated program did not cause a reduction of civil service employees at Ames. In some cases, staff members were redeployed to other programs in order to make the best possible use of available skills. The realignment resulted in a modest shift of contractor effort away from fundamental human factors research toward analysis of integrated systems. The net change in contractor and academic human factors technical support since the beginning of FY 2005 to date is a reduction of about 40 percent. The impact of this reduction was partially mitigated through reassignment of some contractors to other projects. These skill mix adjustments are in line with the requirements of the reformulated Aeronautics program.

ANSWERS TO POST-HEARING QUESTIONS

Responses by Major General William Hoover (Ret.), Co-Chair, National Academy of Sciences' Steering Committee

Questions submitted by Chairman Ken Calvert

Technology Certification

Q1. The Decadal Survey *recommends NASA work closely with the Federal Aviation Administration to ensure that new technologies be certified. Certification work has traditionally been the domain of regulatory authorities which write and enforce operating standards. Why should NASA take on the task of helping FAA develop certification standards?*

A1. The Decadal Survey committee named certification as a barrier to the realization of the next-generation air transportation system. Current certification processes and methods will encumber the transition of new technology into the system.

From the *Decadal Survey*:

> *"As systems become more complex and non-deterministic, methods to certify new technologies become more difficult to validate. Core research in methods and models for assessing the performance of large-scale systems, human-interactive systems, non-deterministic systems, and complex, software-intensive systems, including safety and reliability in all relevant operating conditions, is essential for NASA, because such research is currently beyond the capabilities of regulators such as the FAA."*

It is important to note that the *Decadal Survey* does not encourage NASA to "ensure that new technologies be certified," but rather, to research certification methods and standards in order to improve the speed, reliability, and overall value of the certification process—and to ensure that science and technology necessary to certify new civil aviation technology is available. To be useful, new civil aviation technology must be certifiable, and if the new technology is incompatible with existing certification standards and methods, then NASA should also support research to provide the FAA with the science and technology it needs to develop and validate new certification standards and methods. The proper roles for NASA, according to the *Decadal Survey* are:

- "Systematic documentation and publication of model and design assumptions from the earliest stage of R&T development, to aid in a technology's ultimate certification.
- Ongoing iterative validation of models and design tools—and their specifications—during their development, and verification of models and design tools relative to their specifications.
- Generation of databases and models from empirical data to provide a basis for validation and certification.
- Establishment of community-accepted metrics, criteria, and methods for validation and certification."

Finally, the committee questioned whether the current configuration of federal aeronautics research was optimal for ensuring a high level of technology transition. The report recommended a re-examination of high-level organizational options to assure continued U.S. leadership in civil aeronautics.

Space-Related Research

Q2. What was the committee's rationale for citing the space program as a "lower priority Strategic Objective"?

A2. The focus of this study was on civil aeronautics. The Decadal Survey Committee felt that the major customer of civil aeronautics is the national air transportation system. Certain aeronautical research topics could benefit the space program, but re-entry vehicles and Martian airplanes are of little use to the flying public. Further, the budget of the space program dwarfs the amount of funding available for aeronautical research. The committee felt that prioritizing aeronautics research for space above aeronautics research for aeronautics (1) essentially uses the small and shrinking aeronautics budget to subsidize the much larger budget of the space program, (2) is poor stewardship of the Nation's small aeronautics budget, and (3) disguises the true cost of the space program. All this could be avoided if the space program funded research in all flight regimes (including hypersonics research, which has no civil aviation applications) necessary to support the space program. The committee did see added value in technologies that had benefits to space as well as to civil aeronautics, and felt that including "support to space" as a lesser-weighted strategic objective was a good way to express this.

Questions submitted by Representative Mark Udall

Q1. NASA aeronautics program management has stated that they intend to focus on fundamental aeronautics rather than demonstrators, emphasizing the difference between "experiments" and "demonstrators." What are your views on NASA's planned approach?

A1. The committee believes that demonstrations have made important contributions over the history of aeronautics. At some point—whether labeled a "demonstration" or "experiment"—flight tests are a necessary part of the development process for many important aeronautical technologies. With the advent of more sophisticated system-of-system analysis techniques, physics-based modeling, simulation, etc., expensive single solution point designs of the past can be replaced with more generic validations and data. However, computer simulations still require verification and validation at some point. I personally believe if we are ever going to gain acceptance of game-changing technologies, such as overland supersonic flight, we will need flight demonstrations (or experiments) validate claims that sonic boom sound pressure levels are low enough to be acceptable to the public, regulators, and legislators.

Q2. What is your sense of the outside community's view of the redirection of the NASA Aeronautics program? What, if any, concerns have you heard expressed?

A2. I sense that most of industry and many academics are questioning the relevance of NASA's aeronautics research. NASA is not seeking to engage industry, either by offering useful partnerships and funding, or even just by pursuing research that is of interest to industry. Many academics who are interested in fundamental aeronautical sciences are pleased with NASA's new direction, but those interested in more advanced topics, such as systems research and certification methods, feel that NASA has nothing for them. Overall, many academics are worried that NASA's ability to attract, support, and mentor students may be greatly diminished.

Q3. What did the National Academies' Decadal Survey *conclude about the relative priority that should be given to aeronautics research in support of the President's* Vision for Space Exploration *and other space activities?*

A3. The committee named "Support to Space" as one of the strategic objectives that could be used to evaluate the value of a given technology, but gave this objective a low weight. In terms of apportioning the limited budget available for civil aeronautics, support to space was considered to be less important than capacity; safety and reliability; efficiency and performance; and energy and the environment; and considered to be equal in importance to synergies with defense. As stated in the response to *Majority Question 2,* The Decadal Survey Committee felt that the major customer of civil aeronautics is the national air transportation system. Certain aeronautical research topics could benefit the space program, but re-entry vehicles and Martian airplanes are of little use to the flying public. Further, the budget of the space program dwarfs the amount of funding available for aeronautical research. The committee felt that prioritizing aeronautics research for space above aeronautics research for aeronautics (1) essentially uses the small and shrinking aeronautics budget to subsidize the much larger budget of the space program, (2) is poor stewardship of the Nation's small aeronautics budget, and (3) disguises the true cost of the space program. All this could be avoided if the space program funded research in all flight regimes (including hypersonics research, which has no civil aviation applications) necessary to support the space program. The committee did see added value in technologies that had benefits to space as well as to civil aeronautics, and felt that including "support to space" as a lesser-weighted strategic objective was a good way to express this.

Q4. How would you differentiate the National Academies' Decadal Survey of Civil Aeronautics *from the process that NASA used in coming up with its restructured aeronautics program in January of this year?*

A4. Few details were available about NASA's prioritization process, and its planning sessions were not open to the public, so I cannot address this question in detail. The most obvious difference is in methodology. The National Academies engaged a large sample of the aeronautical community-industry, academia, NASA, and other federal agencies. We clearly documented our process—a process which is transparent, repeatable, and has the flexibility to accommodate changing priorities, such as a new aeronautics policy. The report was subject to the Academies' rigorous external review process. While NASA held listening sessions to gain the input of other stakeholders, the final priorities were decided completely internally. NASA did not release any documents outlining their process and it is unknown what sort of review was used to validate its findings.

Q5. What do you think would motivate industry [e.g., cause it commit serious resources] to work with NASA on aeronautics R&D?

A5. NASA contends that its fundamental research includes applied research. In my opinion, NASA must realize that industry is the major customer for most of its civil aeronautics research, and work to attract industry's attention. NASA must include industry in its planning processes to ensure that research projects are of interest, and that proper hand-off criteria are agreed upon and established. Although industry will easily pick up technology that has a clear business case, NASA and industry should work to identify and agree upon topics that will be of value further down the road. NASA must offer some reciprocation of funds—if industry has to bring all of the money, they would prefer to keep their projects in-house. Finally, NASA must work to provide industry assurance of intellectual rights, where appropriate.

Q6. Earlier this year, the Aircraft Safety Subcommittee of the FAA's R&D Advisory Committee made the following recommendation to FAA management:

"The FAA needs to make an assessment of the impact of the budget cuts in NASA's aeronautics R&D. Subcommittee on Aircraft Safety is concerned that there may be inadequate resources in the FAA's budget for taking on safety-related research that NASA used to perform in the past but won't be funded to cover in the future."

Q6a. Did the Decadal Survey *look at the impact that the budget cuts and reprioritization going on in NASA's aeronautics program are having on aviation safety research?*

A6a. No. The charge of the *Decadal Survey* was to identify technology challenges that need to be addressed, not to review any current NASA programs, or to analyze budgetary issues.

Q6b. Do you share the FAA Aircraft Safety advisory subcommittee's concern that NASA's actions could have negative consequences for government-wide activities related to aviation safety?

A6b. The Decadal Survey Committee identified safety as a major criteria in prioritizing research topics. Based on the their experience, instead of identifying specific "safety" topics as an end unto themselves, the committee felt that safety should be incorporated along every step of the research process in every research and technology challenge.

The committee did not review any specific activities at NASA or the FAA, and cannot comment on the impact of specific budgetary or programmatic actions, many of which took place in parallel with the work of the committee.

Appendix 2:

Additional Material for the Record

Defense News

September 25, 2006

China Tried To Blind U.S. Sats With Laser

BYLINE: VAGO MURADIAN

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China has fired high-power lasers at U.S. spy satellites flying over its territory in what experts see as a test of Chinese ability to blind the spacecraft, according to sources.

It remains unclear how many times a ground-based laser was tested against U.S. spacecraft or whether it was successful.

But the combination of China's efforts and advances in Russian satellite-jamming capabilities that illustrate vulnerabilities to the U.S. space network are driving U.S. Air Force plans to develop new space architectures and highly classified systems, according to sources.

The hardware on the spacecraft can't be changed after they are launched, but software changes can help them weather attacks

Lasers of sufficient power could blind electro-optical satellites like the giant Keyhole spacecraft or even interfere with radar satellites like the Lacrosse, experts said. Blinding, one source said, is different than disabling. It requires enormous power to shoot a laser through the dense lower atmosphere and reach a fast-moving satellite in orbit.

Russian jamming systems are publicly known. In 2003, the Air Force destroyed such a system deployed to Iraq to keep American Global Positioning System (GPS)-guided bombs from finding their targets. The site was destroyed by GPS-guided bombs.

Pentagon officials, however, have kept quiet about China's efforts as part of a Bush administration policy to not anger Beijing, which is a leading U.S. trading partner and seen as key to dealing with North Korea and Iran.

Even the Pentagon's recent China report failed to mention Beijing's tests. Rather, after a contentious debate, the White House directed the Pentagon to limit its concern to one line. In that one line that acknowledges China has the ability to blind U.S. satellites, thanks to a powerful ground-based laser capable of firing a beam of light at an optical reconnaissance satellite to keep it from taking pictures as it passes overhead.

According to top U.S. officials, however, China not only has the capability, but has exercised it. It is not clear when China first used lasers to attack American satellites. Sources would only say that there have been several tests over the past several years.

"The Chinese are very strategically minded and are extremely active in this arena," said one former senior Pentagon official. "They really believe all the stuff written in the 1980s about the high frontier and are looking at symmetrical and asymmetrical means to offset American dominance in space."

China's burgeoning anti-satellite capabilities are further evidence of Beijing's focused military strategy that aims to engage the United States asymetrically, not directly, said to Andrew Krepinevich of the Center for Strategic and Budgetary Assessments, Washington.

Krepinevich points out that China has outlined a set of capabilities it refers to as "Assassin's Mace" to keep U.S. forces in the region at risk and away from China's borders, and tailored to undermine U.S. advantages.

Jamming Predictable

U.S. service officials are not expressing alarm at efforts to counter the U.S. space advantage. They say such moves are predictable and understandable. But they are taking it seriously enough to test ground-based lasers against their own spacecraft to determine their efficacy and plan space architectures that resist such attacks.

The problem, according to sources, is that satellites are large, have predictable orbits that are easy to track and have scant defenses against lasers.

The United States operates three large optical reconnaissance satellites of the three-decade-old Keyhole-series by Lockheed Martin. The loss of any would hurt U.S. space capabilities, sources said, which is why they will be replaced by a large constellation of spacecraft under the Future Imagery Architecture program being executed by Boeing and Lockheed.

Top U.S. officials, among them Air Force Secretary Michael Wynne, declined to comment on whether China has attempted to blind U.S. satellites.

Chinese officials could not be reached for comment by press time.

Wynne acknowledged that the Air Force's space plans are shaped against potential foes who seek asymmetric means to harm a U.S. space network.

The goal, Wynne said, is to minimize the impact that real-life attacks would have on U.S. space capabilities through a networked architecture that can lose nodes but keep functioning.

Wynne stressed that more is at stake than U.S. military superiority. Signals from Air Force GPS satellites are critical to everything from airline and maritime commerce to car navigation systems.

And unlike the 1980's threat from Soviet anti-satellite plans, future space attacks will be limited in scope, Wynne said.

"At the time, the Soviets were always talking about a bald-faced assault," he said. Future "asymmetric attacks are going to be local to try to mask out our capabilities in one region. The trick to winning asymmetrical warfare is to make it irrelevant."

He said a new generation of GPS 3 satellites "will make further assaults and jamming efforts irrelevant."

Doing "space and ISR through very different means ... means asking good questions," he said. "Do 22,200-mile-high orbits make sense? Does an orbital periodicity that is well known to any adversary have any relevance today? What you really want is assured situational awareness, position location and communications capabilities."

Skeptics: Budget Limitations

But analysts, executives and even officials in the Pentagon have criticized the Air Force, arguing that the service is talking a good game but falling short on execution -- largely for lack of budget.

One veteran space industry executive expressed shock at how limited the debate has been about the need to better secure U.S. spacecraft.

The reason, executives and analysts said, is that such safeguards are complicated and expensive, and become targets when programs go over budget or fall behind schedule.

One source said the Pentagon is so thirsty for more bandwidth to handle burgeoning communications demands that it has been short-changing security, which consumes bandwidth.

"It's a tradeoff," said one industry source. "And so far, the pressure has been for capacity over security."

Loren Thompson, an analyst at the Lexington Institute, said the Air Force is making poor investment choices not only in space, but also in intelligence, surveillance and reconnaissance programs.

"The U.S. Air Force's ambitious plan for fielding orbital and airborne reconnaissance systems has begun to come unhinged in the budget process from Space Radar, to missile warning to future radar planes, the whole mission area seems to be melting down," Thompson said.

Wynne contends that space programs are being restructured to rein in cost increases and schedule slips. Wynne also argues that the F-22 fighter's powerful radar and electronic capabilities allow it to perform the roles of larger existing aircraft like the Joint Surveillance Target Attack Radar System, the Airborne Warning and Control System and the Rivet Joint, allowing the service to forgo investment in aircraft that are vulnerable to a new generation of powerful surface-to-air missiles.

"I'm probably the biggest supporter of the F-22 outside the Air Force, and while it's the best fighter ever and can do these jobs, but not as well as dedicated assets that have the ability to stay on station far longer," Thompson said.

"Osama bin Laden is still at large and there are known vulnerabilities to our space systems. In this environment, it's odd that the Air Force is cutting its orbital, manned and unmanned reconnaissance assets while presenting the F-22 as a reconnaissance platform. The point is, where are we deficient, firepower or finding the enemy?"

As for China specifically, Thompson said the country has a right to defend itself.

"If you keep looking over the fence at you neighbor's back yard, you're going to get poked in the eye, so it's not surprising that China might be worried about U.S. forces stationed on their doorstep," Thompson said.

"They don't like it and are figuring out how to poke us in the eye. Now I'm no great admirer of the Chinese leadership, but how would we feel if the Chinese had their aircraft carriers off Long Island. That's why we have to do a better job of protecting ourselves and I'm afraid that's not what we're doing."

The former Pentagon official put it more bluntly.

"The Air Force is trying to put a happy face on this," he said. "It's not that they don't know what do. It's that they don't have the money in their space budget. It's that simple."

Another factor is requirements growth. For example, the Air Force originally envisioned the National Polar Orbiting Environmental Observation Satellite as a powerful new climate spacecraft. But departments across the government added their unique payloads, causing integration challenges and cost growth.

The same happens on classified spacecraft as intelligence agencies pile on payloads. Then there is the challenge of ensuring that the technology on the spacecraft is the best possible given it will be in orbit for a decade or more.

"Unlike an airplane, once you launch something into space you can't upgrade it again, so when it comes to technology, you are often reworking your system to get the best available in there because you know that it's going to be around for a long time once it's in orbit," the former official said.

"So when people talk about cost, that's a piece of it. It's even harder when you're trying to protect yourself against threats over the next 50 years." *

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Inside the Pentagon

October 12, 2006

TOP COMMANDER: CHINESE INTERFERENCE WITH U.S. SATELLITES UNCERTAIN

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Gen. James Cartwright, the top U.S. military officer in charge of operations in space, says the United States has not seen clear indications that China has intentionally disrupted American satellite capabilities.

In an interview last month, Inside the Pentagon asked the U.S. Strategic Command chief about allegations made by some uniformed officials and civilian experts that the Chinese military in recent years has tested the means to harm or destroy American satellites.

"Your [question pertains] to someone actually with intent interfering out there," Cartwright said during the Sept. 21 Pentagon interview. "And we really haven't seen that."

The Marine Corps general declined to address details about the capabilities or actions of specific nations.

But he said it is only "prudent" for the U.S. military to improve its ability to monitor space assets, given the possibility of future meddling.

"You have to expect that any place you put commerce and you put value, there will be competition in that environment," Cartwright told ITP. His command, whose responsibilities also include nuclear weapons and missile defense, is headquartered in Omaha, NE.

The United States relies heavily on satellites for commercial communications, navigation systems and an array of critical military capabilities. The nation owns more than half of the 800 satellites currently in orbit, according to the Union of Concerned Scientists, based in Washington. Military operations rely on space-based commercial communications capacity for up to 80 percent of its needs, says one top space official.

The White House late last week released a 10-page summary of its newly revised space policy, which emphasizes maintaining the ability to utilize space without impediments (see related story).

"Freedom of action in space is as important to the United States as air power and sea power," the official summary states.

A growing Chinese capability to target objects in orbit has proved troubling to a number of defense and intelligence community officials.

In May, the Pentagon sent a report to Congress on Chinese military capabilities that offered little detail about anti-satellite efforts. But it noted, "At least one of the satellite attack systems appears to be a ground-based laser designed to damage or blind imaging satellites."

Defense News, a trade newspaper, last week cited unnamed U.S. officials contending China has actually used lasers on several occasions over the past few years to test an ability to blind U.S. satellites.

"China not only has the capability, but has exercised it," the publication reported Sept. 25.

Asked this week to respond to the assertions contained in the Defense News article, Cartwright said he would not address specifics "because it might lead our adversaries to speculate about our capabilities."

But in his e-mailed response, he said, "The Department of Defense has been aware that China is conducting research to develop ground-based laser anti-satellite weapons."

Cartwright's earlier comments during the Sept. 21 interview "were meant to ensure that your readers were not left with the impression there are nations routinely operating in space with hostile intent against our national assets," the general said this week.

For its part, the Chinese government-dominated media is attempting to refute the trade journal piece.

"The information about China using laser to blind U.S. satellites is entirely a conjecture," states a translated version of an article published online Sept. 28 in Beijing's Huanqiu Shibao, a supplement to the daily newspaper published by the Communist Party's Central Committee. "The United States' exaggeration of China's counter-satellite technology is only an attempt to seek an excuse to justify its development of space weapons."

Back in the United States, several China experts in and outside the government say that while the Chinese interest in space clearly extends to its military sector, evidence of exercises is murkier than portrayed by the Defense News article. Some say basic facts reported in the article are accurate. But others note that events occurring in space that might be interpreted as combat preparation or exercises in fact remain mysterious. The international community can only speculate about motives, these officials say.

Because the details are highly classified, debate over Chinese activities and intentions in space has flared mainly behind closed doors, according to experts.

"Layers and layers of classification" shroud information about satellites the United States has fielded in space, international capabilities to harm those satellites, and actions the U.S. military has taken to protect its space-based assets or potentially harm others, according to one source.

Even for those with top-secret clearances, a considerable obstacle to interpreting Chinese actions in space with confidence is a limited U.S. ability to monitor and investigate what goes on in orbit -- something the military calls "situational awareness."

"We've done a good job so far cataloging what is up there but the time has come to take the next step" -- namely, improving situational awareness, Air Force Gen. Kevin Chilton, head of Air Force Space Command, said in an August conference speech.

Some experts say the United States has detected miniature Chinese satellites placed in orbit nearby U.S. military communications and imaging satellites.

Some are close enough to sensitive U.S. satellites that they could "cause damage if they are packed with conventional high explosives," says John Tkacik, a senior fellow in Asian studies at the Heritage Foundation in Washington.

However, two years ago, analysts with the Union of Concerned Scientists called into question the veracity of Chinese news reports about the potentially "parasitic" microsatellites, cited by the Pentagon in past reports to Congress.

Meanwhile, Chilton seeks a clearer picture on a minute-by-minute basis.

"I want . . . to be able to tell the combatant commander, Gen. Cartwright, the capabilities and owner's intentions of any new object put into space," he said in his conference speech. "I want to know if they maneuver. And if they calve a micro-sat. And if they are a threat to any of our systems."

Chilton said that, in the past, U.S. space officers tracked international launches simply to determine if they were ballistic missiles or satellites deploying into space. If a satellite was launched, the U.S. tracking stopped on the assumption that the orbiter was for a peaceful purpose.

"I say those days are over," the Air Force space commander said. "If it's a space launch, we can't afford to relax."

Until improvements are made, divining the meaning of suspicious events in space is a bit like the Kremlinology that Soviet experts in the West practiced during the Cold War.

"Interpretations are mixed," says one senior military officer, interviewed this week by ITP on condition of not being named. "[There is] much discussion about what was done and not done, but to me the important point is that country's pursuit of the capability."

"There may be a controversy about interpreting various events," agrees another official, who said the situation is analogous to intelligence community debate over pre-war intelligence about the existence of Iraqi weapons of mass destruction.

In last month's interview, Cartwright said the way in which the United States responds to unexplained events in space may affect future relations between world powers.

"Will it turn hostile at any point?" the general asked. "[That] is something that you certainly don't want to hasten by the wrong actions. But you [also] certainly don't want to be disadvantaged by sitting on your hands when you should have been thinking about, gosh, what would be the next step?"

The senior military officer, who demanded anonymity for this article because he was not authorized to speak publicly about this issue, echoed Cartwright's concerns.

"[We] don't want to portray them as the 10-foot-tall 'panda,' but we shouldn't be too naïve about their capability and intent, either," the official said.

"I'm not sure the U.S. government wants to come out and accuse the Chinese of doing this sort of thing unless there is unambiguous evidence," says Michael Swaine, a senior associate at the Carnegie Endowment for International Peace in Washington. For the Bush administration, it is "more urgent" at this time to win Chinese cooperation in imposing sanctions on North Korea following its claim of an Oct. 9 nuclear weapons test and in restraining Iran's nuclear development program, he said.

"It is not necessarily in the U.S. interest to confront [China] with this, at least not publicly," Swaine told ITP in an Oct. 11 interview.

"It would be tragic if paranoia about a China threat were used to accuse them of this kind of highly sophisticated action," Michael Pillsbury, an adviser to Defense Secretary Donald Rumsfeld on Sino-American policy, said this week.

Cartwright says he is using a newly opened Joint Space Operations Center to ensure U.S. satellites, as well as international partners in space, adhere to common "rules of the road" -- much like the government sets and enforces driving behavior and speed limits on American highways.

In the space arena, when the United States detects that something has gone wrong, the first questions typically asked are, "Gee, was it our satellite that wandered off course? Was it someone else's?" Cartwright said. "It's not a . . . pointing-a-finger thing. But it is an understanding of responsibility and making sure that we have some measure [of behavior]. You expect me to stay on the right-hand side of the road when you approach me and that type of thing."

As space becomes more crowded with satellites, the need to enforce common operating rules becomes more urgent, he said. Greater international adherence to those rules could make it easier to interpret any deviations from common practice, according to the general.

"There are 16 or more nations with a demonstrated capability to operate 10 or more satellites on orbit," Cartwright said in his Oct. 11 e-mailed response to questions. "Seven of the 16 nations are non-NATO countries, to include China, Russia, India, South Korea, Indonesia, Brazil and Japan. We expect many more nations to expand their national interests into space and, unfortunately, we anticipate some will challenge the free use of space."

The United States, he said, "is committed to the use of outer space by all nations for peaceful purposes and seeks to cooperate with others, consistent with international space treaty obligations." -- Elaine M. Grossman

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NASA Chief in China to Discuss Space Cooperation

By WARREN LEARY

WASHINGTON, Sept. 23 — The leader of NASA arrives in China on Sunday for a tour of space agency sites, making him the most senior American space official to go to China to discuss possible cooperation between the countries' programs.

Michael D. Griffin, the administrator of the National Aeronautics and Space Administration, has repeatedly cautioned that the tour, which will include Beijing, Shanghai and a desert launching site in Gansu Province, will be an exploratory visit that will not result in any bilateral space agreements or formal partnerships.

"This is a get-acquainted visit that has no preconditions to it," he said recently. "We are going to see things and meet people, and see where that takes us."

China is the third country, after the United States and Russia, to have sent humans into space. It has been seeking more international cooperation in aerospace projects, but the United States has been reluctant. Much of China's program is run by the military, raising concerns about possible technology transfers or other national security issues for any such cooperation.

Working with China in space has also been hampered by other issues under discussion by the two nations, like weapons proliferation, trade agreements, patent and trademark enforcement, and human rights, said a senior adviser at NASA, who spoke on condition that he not be identified.

Recently, though, the American position has begun to shift. When Chinese space officials invited the previous NASA administrator, Sean O'Keefe, to visit their operations two years ago, nothing came of the overture. However, when President Hu Jintao of China visited the United States in April and made the same request of Mr. Griffin, President Bush accepted the invitation.

"There has been a policy decision by the Bush White House to do this," said John Logsdon, the director of the Space Policy Institute at George Washington University. "It's part of an effort to engage China, to open a dialogue that may influence their policies in other areas. But it's starting slowly and deliberately."

Accompanying Mr. Griffin on the trip is William Gerstenmaier, the associate administrator for space operations, Michael F. O'Brien, the assistant administrator for external relations, and Shannon Lucid, a veteran astronaut. Ms. Lucid, who is the daughter of Baptist missionaries, was born in Shanghai and is returning to China for the first time since her childhood.

The group will meet Sun Laiyan, the administrator of the China National Space Administration in Beijing and tour aerospace operations and science centers there before going to Shanghai to visit space manufacturing plants there.

Also scheduled on the five-day trip is a visit to the Jiuquan Satellite Launch Center, an extensive rocket-launching complex from which the Chinese prepare and fly their manned spacecraft.

The Chinese launched their first manned spacecraft, Shenzhou, in October 2003, sending one astronaut into orbit for a day. In 2005, a Shenzhou with a two-person crew spent five days in orbit. Chinese authorities said their third mission, set for fall 2007, will send up three astronauts and will include spacewalks.

This year, Chinese officials visiting the United States outlined their plans for an extensive program of manned and unmanned programs, including orbiting a small, staffed space station by 2015 and establishing a moon program that includes sending a robotic orbiter next year, a lunar rover in 2012 and a lander that would return a moon sample to Earth in 2017. While there are no immediate plans to do so, Chinese officials also have expressed interest in sending humans to the moon.

Vincent G. Sabathier, a senior fellow on space issues at the Center for Strategic and International Studies in Washington, said that in the past, the United States had tried to contain Chinese ambitions in space but that this was no longer possible. China has major space agreements with Russia, Europe and most other nations with space programs, and is clearly striving to have a major role in the area, he said.

"The Chinese are going their way and have a strategy in place," Mr. Sabathier said. "They want to work with the United States and be accepted as a major player, and the U.S. is obviously now seeing some potential in working with them, which explains Mr. Griffin's trip."

Mr. Sabathier and other experts said the composition of Mr. Griffin's team, including the head of NASA's human space flight program and Ms. Lucid, whose five trips to space included a long stay aboard the Russian Mir space station, suggests that some type of cooperation in space may be under consideration.