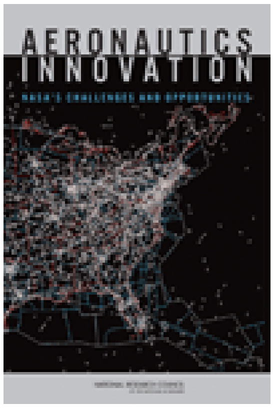

Aeronautics Innovation: NASA's Challenges and Opportunities

Stephen A. Merrill, Editor, Committee on Innovation Models for Aeronautics Technologies, National Research Council

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AERONAUTICS INNOVATION: NASA'S CHALLENGES AND OPPORTUNITIES

Committee on Innovation Models for Aeronautics Technologies

Board on Science, Technology, and Economic Policy

Policy and Global Affairs

Stephen A. Merrill, Editor

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Preface

The Aeronautics Research Mission Directorate (ARMD) of the National Aeronautics and Space Administration (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. Application 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 (FAA). To help produce a more robust innovation climate, ARMD 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 National Academies assembled a committee composed of experts in private-sector technology management, public policy and administration, and economics. Included were people experienced not only in different areas of aeronautics technology development but also in information technology, optoelectronics, and materials. The committee organized two public workshops. Participants in the first workshop included experts from industry, government, and academia who discussed the application of modern innovation techniques to a broad range of entities. The second workshop focused more directly on the aviation sector. Participants included senior industry executives, academic experts and consultants, former high-level NASA and FAA officials, and representatives from the Air Force and the FAA-based interagency Joint Planning and Development Office, charged with coordinating federal agency efforts to plan and implement a 21st century air traffic control system in the United States.

Committee members and staff also visited three of the NASA research establishments engaged in aeronautics R&D: the Ames Research Center in California, the Glenn Research Center in Ohio, and the Langley Research Center in Virginia. ARMD has direct administrative responsibility for Glenn and Langley as well as the Dryden Research Center in California; Ames was recently transferred to the NASA science program office. At each of the locations we visited, we interviewed top center managers as well as R&D program and project managers. These interviews were supplemented by in-person or telephone discussions with other individuals knowledgeable about NASA and the aerospace industry. Of course, NASA headquarters officials participated in the workshops and committee staff conferred with them throughout the project.

The committee thoroughly reviewed the large volume of reports in the past few years on the aerospace industry and government policies affecting it. These efforts ranged from broad assessments of the future of the U.S. industry by government commissions and such private organizations as the Aerospace Industries Association to technical evaluations of the quality of NASA's aeronautics program by committees assembled under the National Academies' Aeronautics and Space Engineering Board. The reports conclude that 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. Previous National Academies' reports have found that NASA's R&D portfolio generally exhibits high technical merit. Our committee accepted this judgment, as we lacked the breadth of expertise to make an independent evaluation of the technical merit of the agency's activities. Finally, the committee reviewed the recent budget history and personnel profile of the NASA aeronautics program, including congressional testimony on the President's FY 2006 budget request.

A vivid picture emerged from the workshops, center visits, consultations, literature review, and budget analysis. Despite strong private-sector support for a broad and robust federal government role in civil aeronautics technology development, Congress and recent administrations have not come to terms on what are widely regarded as nationally important NASA aeronautics missions and the level of resources needed to address them effectively and in a timely fashion. On the contrary, the budget has declined steadily over a seven-year period. In response, ARMD and its predecessors have attempted to do as much or more with less, spreading resources too thinly to ensure their effectiveness and the application of the R&D results. This has been a growing problem for several years, but it was brought home most forcefully by the President's FY 2006 request for a sharply reduced ARMD budget, forcing a radical scaling back of the Vehicle Systems Program (VSP) R&D to pursue only a few of the technology development activities in its portfolio. Furthermore, the administration's out-year budget projections to 2010 showed a 50 percent decrease in the aeronautics R&D budget and personnel overall. Although arguably beyond our purview, these circumstances were too central to the viability of NASA's aeronautics program for our committee to ignore, even though they occurred in the final stages of our deliberations.

As described in the report's first chapter, the budget proposal exposed the lack of agreement between government and the aeronautics community about the federal government's role in civilian aviation generally and NASA's role in aviation technology in particular. Former Associate Administrator Victor Lebacqz acknowledged as much in defending the President's FY 2006 budget request before the House Science Committee in March 2005. He said that currently there are two contending points of view. One, reflected in the reports described earlier, is that the aviation sector is critically important to national welfare and merits government support to ensure future growth and market share despite fierce international competition. This implies an expansive public and private research and development program. The other, reflected in the White House's budget submission, is that as the aviation industry approaches maturity and commoditization, the government can retrench and leave technology development to the private sector. Interestingly, he neglected to mention the public good objectives—mobility, safety, and environmental protection—served by NASA's R&D involvement.

The proposed retrenchment had a galvanizing effect. In the FY 2006 Appropriations Act, congressional appropriators rejected the proposed cut and restored the ARMD budget to its FY 2005 level or slightly above. At the same time, the authorizing committees secured passage of the NASA Authorization Act (P.L. 109-155) calling on the administration to prepare a policy statement on aeronautics as a basis for further discussion with Congress. Meanwhile, a new NASA administrator and associate administrator withdrew the proposed scaling back of the VSP program and set to work on a new plan for ARMD.

These are encouraging signs that a policy consensus could emerge and a potentially fatal retrenchment be avoided. But in the near future there is unlikely to be a large infusion of new resources. Given that the program will probably continue to operate in a highly resource-constrained environment, the first principle of modern innovation management is highly relevant. It is that the highest priority projects need to be identified and the less important projects winnowed out. Beyond that, best practices and techniques for NASA's aeronautics R&D management are needed in three areas—transition planning, financial management, and personnel management. These are elaborated in Chapter 2 of the report. We think that these principles and practices, if applied consistently to a more focused portfolio of activities, could facilitate the implementation of NASA-developed technologies.

Our committee also heard suggestions for reorganization of the NASA aeronautics program. These included the creation of an agency operating in the mode of the Defense Advanced Research Projects Agency (DARPA)—that is, an expert staff of managers outsourcing projects to firms and universities. Another suggestion was to convert the research centers into contractor-operated institutions, as in the Department of Energy. A third proposal was to raise the stature and increase the independence of the aeronautics program within NASA, perhaps along the lines of the FAA's relationship to the Department of Transportation. Evaluating these options was not our assigned task, although we observe some characteristics of DARPA that raise questions about whether it is an appropriate model for NASA. In any case, we concluded that they are distinctly secondary to the question of what the federal government's role should be in developing new technologies for the nation's air transportation system. Failing to answer that question puts the program on a glide path to irrelevance.

This volume has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Academies' Report Review Committee. 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 process.

We wish to thank the following individuals for their review of this report: Jeremiah Creedon, Old Dominion University; George Donohue, George Mason University; Steve Flajser, Loral Space Systems; Richard Golaszewski, GRA, Inc.; Michael Leahy, Air Force Research Laboratory; Earll Murman, Massachusetts Institute of Technology; Dorothy Robyn, The Brattle Group; and David Whelan; Phantom Works, Boeing.

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 John Ahearne, Sigma Xi, the Scientific Research Society, and Thomas Young, Lockheed Martin Corporation, Retired. Appointed by the National Academies, they were 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.

Alan Schriesheim, *Chair*
Committee on Innovation Models for Aeronautics Technologies

List of Acronyms and Abbreviations

AIA	Aerospace Industries Association
ARMD	Aeronautics Research Mission Directorate (NASA)
ARC	Ames Research Center (NASA)
AFRL	Air Force Research Laboratory (DOD)
ASME	American Society of Mechanical Engineers
ASP	Airspace Systems Program (NASA / ARMD)
AvSSP	Aviation Safety and Security Program (NASA / ARMD)
ATC	air traffic control
ATM	air traffic management
ATO	Air Traffic Organization (FAA)
COCO	contractor-owned contractor-operated research center
DARPA	Defense Advanced Research Projects Agency (DOD)
DFRC	Dryden Flight Research Center (NASA)
DHS	U.S. Department of Homeland Security
DOD	U.S. Department of Defense
DOT	U.S. Department of Transportation
EPA	U.S. Environmental Protection Agency
FAA	U.S. Federal Aviation Administration (DOT)
FFRDC	federally funded research and development center
FY	fiscal year
G&A	general and administrative expenses
GOCO	government-owned contractor-operated research center
GOGO	government-owned government-operated research center
GPS	global positioning system
GRC	Glenn Research Center (NASA)
HR	human resources
JPDO	Joint Planning and Development Office (FAA)
LRC	Langley Research Center (NASA)
MOA	memorandum of agreement
MOT	management of technology
MOU	memorandum of understanding
NACA	National Advisory Committee on Aeronautics
NASA	National Aeronautics and Space Administration
NIA	National Institute of Aerospace
NIH	National Institutes of Health
NOAA	National Oceanographic and Atmospheric Administration
NSF	National Science Foundation
NSTB	National Transportation Safety Board
OMB	Office of Management and Budget (Executive Office of the President)
OSTP	Office of Science and Technology Policy (Executive Office of the President)
QFD	quality function deployment
PATCO	Professional Air Traffic Controllers' Association

R&D	research and development
RFP	request for proposals
ROA	remotely operated aircraft
RTP	research transition plan
SEWP	science and engineering workstation procurement
STEP	Board on Science, Technology, and Economic Policy (The National Academies)
TMA	traffic management advisor
TQM	total quality management
TRL	technology readiness level
TSA	Transportation Security Administration (DHS)
UARC	university-affiliated research center
UAV	unmanned air vehicle
USDA	U.S. Department of Agriculture
VSP	Vehicle Systems Program (NASA/ARMD)
WCF	working capital fund

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Summary

NASA's Aeronautics Research Mission Directorate (ARMD) supports research and development in advanced airframe, engine, emissions, air safety, and air traffic control technologies. These diverse missions predate the creation of NASA in 1958 and have survived many changes in the industry. They are still recognized as important governmental functions by recent public bodies, such as the Commission on the Future of the Aerospace Industry, and private organizations ranging from the National Academies to the National Institute of Aerospace.

Reviews of NASA's record and research portfolio note a number of impressive accomplishments and in general praise the quality of research performed in advanced materials, propulsion, aerodynamics, aviation safety and emissions, controls systems, human factors, and many other areas. Nevertheless, there is ongoing concern about the translation of NASA's aeronautics research results into product and systems innovations that improve the air transportation system. This is not surprising in view of the enormous management challenges the program faces, including the following:

- Unlike in most of its space-related activities, NASA has no institutional responsibility, resources, or ability to directly implement technologies developed by the aeronautics program. Rather, implementation is dependent on external customers such as airframe, engine, and other aircraft component manufacturers and assemblers and the regulatory and operational arms of the Federal Aviation Administration (FAA).
- These external customers have exceedingly diverse goals, needs, time horizons, and technical capabilities. The missions range from supplying quasi-public goods (air transportation safety) to supporting commercial activities. The users range from highly sophisticated aircraft, engine, and other component manufacturers to a federal government entity, such as the arm of FAA operating the nation's air traffic control system, with limited incentives and technical capabilities to innovate.
- What NASA's customers and users have in common, however, is that they are operators, managers, and developers of complex systems (aircraft, engines, avionic subsystems, air traffic control hardware and software), entailing the integration of many technology advances. Discrete technologies, however technically successful, may not be incorporated into these systems. In that case, they do not represent innovations.
- Among federal R&D agencies, NASA supports a very broad range of activities—from basic research through demonstration of specific technologies.
- NASA aeronautics is overshadowed in resources, managerial attention, and political support by the agency's principal mission of space exploration and discovery. The difference in status between aeronautics and space is if anything more pronounced since President Bush's announcement of a new mission to return human beings to the moon and eventually send them on to Mars.

In addition to these facts of life, NASA aeronautics officials also recognize that there have been advances in private- and public-sector innovation management that might be applied or adapted to their tasks. For these reasons, ARMD asked the National Academies' Board on Science, Technology, and Economic Policy to recommend tools, techniques, and practices that might facilitate and accelerate aeronautics innovation involving the results of NASA's R&D activities. Interpreting the charge to focus on the deployment of NASA-developed technologies by users outside the agency, the National Academies appointed an ad hoc study committee composed of academic experts in technology management and public administration and people experienced in the development of a variety of technologies directly and indirectly related to aeronautics.

PUBLIC POLICY AND PROGRAM PRIORITIZATION

In attempting to address this task, the committee was soon struck by the growing discrepancy between the needs said to be served by the program and the resources available to it. 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. This has been a growing problem for several years, but administration budget plans for FY 2006 and succeeding years—anticipating a 50 percent reduction in the aeronautics R&D budget and personnel overall by 2010— have made it extremely acute.

Modern innovation management in a resource-constrained environment has as a first principle identifying and adequately supporting the highest priority projects and winnowing out less important ones. Within ARMD this process has only recently begun. Unless it is guided by a clear strategy, carried out in close consultation with all stakeholders and extended to all areas of aeronautics in which NASA is currently involved, other managerial advice is of little utility in helping meet the nation's needs.

The committee was neither 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 enterprise should be organized. We do offer the following general advice on what a national policy should entail and how prioritization of the activities supporting it should proceed.

Congress and the executive branch should engage in a dialogue to articulate national goals in civil aviation and the corresponding public sector role(s). 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).

- NASA's first order of business in promoting 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, personnel, and technical capabilities. This, in turn, should lead to a prioritization of programs and projects involving the research centers, external grantees, and contractors. The result may be a reduced mission scope and portfolio, but one with greater impact on innovation in air transportation.
- The portfolio should reflect stakeholder needs. There should be ongoing consultation with customers and users.
- 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. NASA should continue to undertake core competency reviews and explicitly include aeronautics among the highest priority competencies. Within aeronautics, the ranking of competencies should take into account world leadership in technology, public additive value, and skills enabling partnerships and processes of transitioning R&D results.
- The portfolio should be balanced between near-term needs and longer term investments required to achieve transformational national capabilities. Externally imposed requirements (e.g., through congressionally directed funding) limit management decision making and prioritization flexibility, but they are a fact of life, perhaps especially in an environment in which the mission is diffuse or uncertain. NASA should optimize its ability to use such projects productively.

The lack of agreement on the future direction of the aeronautics program has made it difficult for the committee to comply with ARMD's request to recommend practical measures to enhance the implementation of NASA-developed technology. Obviously, the advice would not be the same for projects designed to yield fundamental knowledge and projects undertaken for clearly identified customers leading to prototype technologies, for example for fuel-efficient engines or air traffic control modernization. A decision to confine NASA's R&D program to fundamental research would shift the focus of attention away from the management of the R&D process and the hand-off of resulting technologies and toward the dissemination of fundamental knowledge, for example, via peer-reviewed publications, participation in scientific and technical meetings, and training of entrants into the professional workforce. In other words, it would call for a study very different from the one we have conducted.

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 of industry stakeholders, without which the program cannot compete effectively for resources in a constrained budget environment. Moreover, the areas of public good in which the argument for government involvement is strongest—safe, efficient air traffic management and environmentally benign aviation operations—are arguably the areas in which users are more dependent on outside suppliers to deliver fairly well-proven technologies and in which NASA's technical capabilities are in some respects superior. These are also areas where the market is unlikely to produce the optimum level of innovations. For example, companies will innovate to comply with environmental standards, but they may not conduct R&D to improve a standard or to determine where the standard should be set. In terms of aviation system capacity, incumbent operators may benefit from a scarcity of capacity that inhibits competitive entry and thus may not have the incentives to conduct the R&D necessary to expand system capacity. Thus, to sustain its relevance and support, ARMD should have a portfolio quite diversified in terms of the stage of technology being developed, even if that means the portfolio will be reduced because the costs of technology demonstrations, prototype development, and other activities to reduce the risks of applying new technology can be high.

If the aeronautics R&D program is more strategically focused, the committee thinks 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 prioritizing 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, research managers , 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 should work aggressively to solidify its reputation as a trustworthy, reliable partner.
- The Joint Planning and Development Office (JPDO), the multiagency 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 we found the concept sufficiently promising to consider employing it 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 secondment of personnel to and from its several research centers and its external partners as tools 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 midstream 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.

1

National Aviation Needs and the Federal Role

PRIVATE-SECTOR PERSPECTIVE

World leadership in air transportation and aircraft manufacturing is widely viewed as a cornerstone of U.S. economic welfare and national security. U.S. commercial air transportation handled over 40 percent of total U.S. freight by value,[1] and domestic flights drew nearly 600 million business and private passengers in 2003,[2] constituting the backbone of the U.S. travel industry.[3] General aviation carries up to 150 million additional passengers per year.[4] In its 2004 report on aerospace research at the National Aeronautics and Space Administration (NASA), the National Academies' Committee for the Review of NASA's Revolutionize Aviation Program called air transportation "vital to the U.S. economy and the well-being of its citizens."[5]

Aviation's national economic impact does not stop with the air transport system. Aerospace exports made up approximately 27.5 percent of all 2003 U.S. exports in the category that the U.S. Department of Commerce labels "advanced technology products." In that year, trade in airplanes and parts delivered a surplus to the United States of $21.1 billion, which significantly defrayed a deficit of $47.9 billion in all other advanced technology categories.[6] As for its military significance, the Commission on the Future of the United States Aerospace Industry, reporting to the President and to Congress in November 2002, declared a healthy U.S. aerospace industry to be "one of the primary national instruments through which [the U.S. Department of Defense] will develop and obtain the superior technologies and capabilities essential to . . . maintaining our position as the world's preeminent military power."[7]

For the Aerospace Commission and many other industrial and academic groups, recent signs that the nation's preeminence in aviation may be imperiled have occasioned deep concern. At least 11 studies of U.S. activity in aeronautics published over the past half decade by the National Academies, as well as various industry and government bodies have repeatedly called attention to the vulnerability of the United States' traditional leading position. In its final report, the Aerospace Commission stated that "the critical underpinnings of this nation's aerospace

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[1] *Anyone, Anything, Anywhere, Anytime: Final Report of the Commission on the Future of the United States Aerospace Industry* (2002), p. 1-2.
[2] The projected 2004 total, as of March 2005, was 635 million. Air Transport Association, available at http://www.airlines.org/econ/d.aspx?nid=1032.
[3] Travel Industry Association of America, preliminary figures exclusive of international passenger fares, available at http://www.tia.org/Travel/econimpact.asp.
[4] *Final Report of the Commission*, p. 2-1.
[5] National Research Council, *Review of NASA's Aerospace Technology Enterprise: An Assessment of NASA's Aeronautics Technology Programs* (Washington, DC: National Academies Press, 2004), p. 5.
[6] Charles W. McMillion of MBG Information Services, analyses of U.S. Department of Commerce data. [I am seeking a complete set of comparable figures for 2004. I do not yet have a figure for the percentage of ATP exports attributable to aerospace exports in 2004; the 2004 surplus in airplanes and parts was $23.7 billion, while the overall ATP deficit in 2004 was $60.7 billion—kj.]
[7] *Final Report of the Commission*, p. 4-4. The Commission on the Future of the United States Aerospace Industry is hereafter referred to as the Aerospace Commission.

industry are showing signs of faltering" and warned bluntly, "We stand dangerously close to squandering the advantage bequeathed to us by prior generations of aerospace leaders."[8] Most recently, 250 members and affiliates of the National Aerospace Institute, in a report commissioned by Congress, declared the center of technical and market leadership to be "shifting outside the United States" to Europe, with a loss of high-paying jobs and intellectual capital to the detriment of U.S. economic well-being.[9]

A consensus emerges in these reports that the United States must overcome a series of major challenges—to the capacity of its air transportation system, the industry's ability to compete for international sales, its ability to reduce noise and emissions, and the air transportation system's safety and security—if the nation's viability in this sector, let alone international leadership, is to be ensured.

The reports highlight the following problems, among others:

A strained air transportation system. Air transportation in the United States has, in a sense, fallen victim to its own popularity, "reaching capacity, resulting in increased delays and costs for both passengers and shippers."[10] Even before the months leading up to September 11, 2001, a period of growing demand, passenger airlines' on-time records were deteriorating. "Aviation's speed advantage is now nearly lost over shorter distances," the Aerospace Commission noted in its 2002 report. For trips less than 500 miles, doorstep to destination travel speed is between 35 and 80 miles per hour.[11] Barring improvement of the transportation system, the Aerospace Commission estimated that delays will cost the U.S. economy an estimated $170 billion for the period 2002-2012, and their annual cost has been predicted to exceed $30 billion by 2015.[12]

Demand represents only one side of the equation. The air traffic management system, although generally judged to be safe, reliable, and capable on the whole of handling today's traffic flow, relies on 1960s technology and operational concepts and is resistant to innovation.[13] Along with other factors, such as airport runway capacity, it is a severe constraint on expansion in the future. In a 2003 report, a National Academies' committee was emphatic: "Business as usual, in the form of continued, evolutionary improvements to existing technologies, aircraft, air traffic control systems, and operational concepts, is unlikely to meet the challenge of greatly increased demand over the next 25 to 50 years."[14]

Increasing competition in commercial aircraft. A view common to several of the reports is that European competition, which has already eroded U.S. dominance of commercial aircraft sales, threatens one of the nation's few standouts among value-added exports. The U.S. share of this global market plummeted from 71.l percent in 1999 to 50.7 percent in 2003, while the

[8] *Final Report of the Commission*, p. vi.
[9] National Aerospace Institute, *Responding to the Call: Aviation Plan for American Leadership.* (2005).
[10] *Final Report of the Commission*, p. 1-5.
[11] *Final Report of the Commission*, p. 2-5.
[12] *Final Report of the Commission*, p. 2-5.
[13] *Final Report of the Commission*, p. 1-5.
[14] National Research Council, *Securing the Future of U.S. Air Transportation: A System in Peril.* (Washington, DC: National Academies Press, 2003), p. 9.

market share of rival Airbus climbed over the period from 28.9 to 49.3 percent.[15] Military aerospace capabilities, assessed as "robust" by the Aerospace Commission, were nonetheless deemed to be at significant risk owing to their reliance on platforms and an industrial base—measured in both human capital and physical facilities—that are aging and "increasingly inadequate."[16]

One indicator of the aerospace industry's health, total U.S. employment, in February 2004 hit a 50-year low of 568,700—a level more than 57 percent below the peak of 1.3 million it had reached in 1989.[17] "Aerospace sector market capitalization, research and development investments, and return on investments/assets are down and consolidations are up . . . ," the Aerospace Commission noted. "Jobs are going overseas."[18] Although advanced aircraft and air traffic management systems could be procured from foreign suppliers if U.S. manufacturers fail to remain competitive, according to the American Society of Mechanical Engineers that could mean forfeiting the "important national security and economic benefits" that "the supremacy of the U.S. aeronautics industry provides."[19]

Environmental degradation. Although a half century of effort has paid off in significant reductions of both the noise and emissions emanating from the turbine engine, the growth of air traffic over the period has more than offset these fruits of technological progress. In fact, objections to aircraft noise and emissions have been the primary barriers to building new airports or adding new runways at existing airports,[20] both of which are key to relieving pressure on the U.S.'s overburdened air transportation system.

Safety and security concerns. The U.S. air transportation system has an excellent safety record: between mid-November 2001 and mid-December 2004, U.S. commercial aviation, both passenger and cargo, saw a total of 36 fatalities resulting from four mishaps.[21] Although the possibility exists that increased demand over the next 25 to 50 years could result in more accidents, a National Academies committee points out that, in the past, safety improvements have been able to reduce the total annual number of fatalities from commercial aircraft accidents despite increased demand.[22] There is, however, little assurance that historical trends will continue uninterrupted. The events of September 11, 2001, did more than show the vulnerabilities of the air transportation system; they focused attention on new homeland security requirements that call for system capabilities not previously anticipated.

TECHNICAL REQUIREMENTS

Of the dozens of recommendations advanced in the reports described above, some relate to generalized goals such as "leadership," "coordination," and "vision," others to specific policy areas, such as trade and government regulation. Nevertheless, collectively the reports attribute

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[15]Percentages reflect the dollar value of deliveries; statistics, compiled by Richard Aboulafia of the Teal Group, quoted in *New Technology Week*, July 12, 2004, p. 7.
[16]*Final Report of the Commission*, p. 4-2.
[17]Aerospace Industries Association, available at http://www.aia-aerospace.org/issues/subject/employment_facts.cfm
[18]*Final Report of the Commission*, p. 1-5.
[19]*Securing the Future*, p. 59.
[20]*Final Report of the Commission*, p. 2-13.
[21]National Transportation Safety Board, available at www.ntsb.gov.
[22]*Securing the Future*, p. 9.

an important role to new technology, identifying numerous technical requirements for meeting each of the challenges that the aerospace sector now faces.[23] There is no suggestion that the civil aviation system as a whole, despite its origin over 100 years ago, is a mature sector subject to mainly incremental technical improvements. Some of the technologies identified have application primarily in one of the four major areas of challenge: modernizing the air transportation system, improving aircraft performance, curtailing environmental impacts, or enhancing safety and security. Others, crucial in more than one area, may be seen as playing an enabling role across the board. In any case, the interrelation of these four areas is such that improvement in each can be affected by improvement—or by lack of same—in one or more of the others. Collectively the reports seem to place the most emphasis on the following general technical capabilities or enabling technologies:

Modeling and simulation. The National Academies' Committee on Aeronautics Research and Technology for Vision 2050 included in its report a set of detailed recommendations that, it promised, "would provide the long-term systems modeling capability needed to design and analyze evolutionary and revolutionary operational concepts and other changes to the air transportation system."[24] A second Academies panel, the Committee on Breakthrough Technology for Commercial Supersonic Aircraft, foresaw modeling and computer simulation as a significant factor in lowering manufacturing costs, which could help make commercial supersonic aircraft economically successful.[25] Taking a broad view of their potential, the Aerospace Commission projected modeling and simulation, among other applications of information technology, as contributing not only to automating and integrating the air transportation system but also to reducing aviation transit time, fatal accident rates, noise and emissions, and technology-to-system transition time.[26]

Human factors. The National Academies' Committee for the Review of NASA's Revolutionize Aviation Program, in assessing NASA's efforts on aviation safety, described human factors as critical and in need of more support.[27] With specific reference to designing supersonic aircraft, studying the human response to shaped waves was judged necessary, both to assist vehicle design research and to validate new regulatory standards.[28] Describing a future that "will involve much more automation" at the levels of both the individual aircraft and the total air transportation system, the Academies' Committee for Aeronautics Research and Technology for Vision 2050 called for a focus on efforts to design synergistic partnerships between humans and automation that result in better performance in all operating conditions than either could achieve alone.[29] The Aerospace Commission, concurring that human factors research could help "enhance performance and situational awareness . . . in and out of the

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[23]For a synthesis of the recommendations apart from those contained in the more recent National Institute of Aerospace report, see Logistics Management Institute, Working Paper NS 454, Response to Reports on U.S. Air Transportation: Assessment of Recommendations (April 2004).
[24]*Securing the Future*, p. 25.
[25]National Research Council, Committee on Breakthrough Technology for Commercial Supersonic Aircraft, *Commercial Supersonic Technology: The Way Ahead* (Washington, DC: National Academy Press, 2001), p. 34.
[26]*Final Report of the Commission*, p. 9-9.
[27]*Review of NASA's Aerospace Technology Enterprise*, p. 75.
[28]*Commercial Supersonic Technology*, p. 18.
[29]*Securing the Future*, p. 11.

cockpit,"[30] predicted it would be a "primary contributor" to tripling the capacity of the U.S. air transportation system by 2025.[31]

Distributed communications networks. "New integrated air, space and ground networks will enable us to acquire large volumes of data, process that data and then make it available to decision makers anywhere in the world, in near-real time," the Aerospace Commission stated, envisioning applications from cyber security to military logistics to vehicle design.[32] To this end, the Academies' Committee for the Review of NASA's Revolutionize Aviation Program recommended exploration of "revolutionary concepts" related to distributed air-ground airspace systems, including the distribution of decision making between the cockpit and ground systems and reorganization of how aircraft are routed, with significant implications for airspace usage and airport capacity.[33] The Academies' Committee on Aeronautics Research and Technology for Vision 2050, recommending research targeting such "[g]eographically distributed activities," named a variety of specific requirements with multiple applications and benefits.[34]

Examples of specific technological requirements identified by the panels are shown in Box 1-1.

BOX 1-1
Technical Needs of Aeronautics

Air Transportation System

- boosting the security and reliability of voice, data, and ultimately video connections to in-flight aircraft
- increased use of satellites in handling traffic flow
- use of synthetic vision, cockpit display of traffic information, and controller displays to improve awareness of aircraft separation
- prediction and direct sensing of the magnitude, duration, and location of wake vortices
- safety buffers to account for monitoring failures and late detection of potential conflicts
- accommodating an increased variety of vehicles (e.g., unpiloted, tilt-rotor, lighter-than-air)

Aircraft Performance

- improved propulsion systems, both the evolution of high-bypass turbofan engines burning liquid hydrocarbon fuels and the development of engines using hydrogen as fuel
- new airframe concepts for subsonic transports, supersonic aircraft, runway-independent air vehicles, personal air vehicles, and uninhabited air vehicles
- composite airframe structures combining reduced weight, high damage tolerance, high stiffness, low density, and resistance to lightning strikes
- high-temperature engine materials and advanced turbomachinery

[30] *Final Report of the Commission*, p. 9-7.
[31] *Final Report of the Commission*, p. 9-9.
[32] *Final Report of the Commission*, p. 9-3, 9-4.
[33] *Review of NASA's Aerospace Technology Enterprise*, p. 46.
[34] *Securing the Future*, p. 16.

- enhanced airborne avionic systems
- the application of nanotechnology for advanced avionics and high-performance materials
- passive and active control of laminar and turbulent flow on aircraft wings
- tools to reduce the need for costly hardware testing

Environmental Impacts

- low-emissions combustor technology to reduce NO_x emissions and particulate matter
- alternative sources of energy for application to aviation
- structures and materials to reduce drag and improve aerodynamics
- understanding of aviation's effect on climate and the need to balance NO_x and CO_2 emissions
- improved dispersion models
- a standardized method for measuring particulate emissions
- engine and airframe noise reduction technologies
- testing of technology for reducing sonic boom

Safety and Security

- *fault-detection and control technologies to enhance aircraft airworthiness and resilience against loss of control in flight*
- prediction, detection, and testing of propulsion system malfunctions
- technologies to reduce fatalities from in-flight fires, postcrash fires, and fuel tank explosions, including self-extinguishing fuels
- systems using synthetic vision and digital terrain recognition to allow all-weather visibility
- technologies to reduce weather-related accidents and turbulence-related injuries
- understanding human error in maintenance
- blast-resistant structures and luggage containers
- improved technology for passenger screening
- intelligent autopilots able to respond to anomalous flight commands
- reduced vulnerability of global positioning system (GPS) guidance

THE FEDERAL GOVERNMENT'S ROLE IN TECHNOLOGY

A significant federal role in aviation research, development, testing, and evaluation has paralleled the history of flight. Wartime requirements have greatly expanded that role, but it has also influenced civil aviation developments. The numerous commissions and panels that have issued reports in recent years share the view that a substantial federal role is still appropriate, not only in relation to public goods that will not be provided by the private sector—airspace management for mobility and commerce, safety and security, and environmental protection—but also in the development of new aircraft and engine technologies that exceed the time horizon and risk profile of private producers.

Today that role is highly dispersed among many federal agencies—the military services and the Defense Advanced Research Projects Agency (DARPA), NASA, the Federal Aviation Administration (FAA) and other parts of the Department of Transportation, the National Science

Foundation (NSF), the Transportation Security Agency of the Department of Homeland Security, the Department of Health and Human Services, the Environmental Protection Agency (EPA), and the National Oceanographic and Atmospheric Administration.[35] But NASA is in many respects the principal sponsor. When it was established by the Space Act of 1958, NASA absorbed the National Advisory Committee on Aeronautics (NACA), chartered in 1915 (operational in 1917) to coordinate private and public aeronautics research. According to NSF surveys of federal agencies' basic and applied research spending, NASA accounted for 56 percent of the federal investment in aeronautical engineering in 2001.[36]

The Scope and Quality of NASA's R&D Program

NASA has a broader portfolio of R&D activity than any of the other agencies with projects in each of the four areas described above—air traffic management, aircraft and propulsion, emissions and noise reduction, and safety and security.[37] The National Academies' Committee to Review NASA's Revolutionize Aviation Program in 2003 enumerated 15 major projects encompassing 51 subprojects and a total of 23l tasks. For example, in the area of airspace management, the program has aimed at moving the air traffic management system away from sector-specific human control to a much more highly automated system-wide control system while also dealing with airport congestion through work on dynamically reconfigurable runways and smart, nontowered airports. In the area of vehicle systems, the program has aspired to contribute to "revolutionary new air vehicles," through development of

- intelligent turbine engines with significantly reduced emissions;
- airframe and engine noise reduction technology;
- ultralight smart materials and structures, aerodynamic concepts, and lightweight subsystems;
- an unmanned air vehicle (UAV) capable of routine operation in the national airspace;
- controls enabling reduced or no human intervention; and
- other technologies contributing to the goal of a "feeling, seeing, sensing, sentient air vehicle."

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[35]As we observe again at the end of this chapter, coordination of aeronautics R&D has been a recurrent theme of the reports discussed above. The most elaborate proposal, by the Commission on the Future of the U.S. Aerospace Industry, called for the establishment of a multiagency task force, the Next-Generation Air Transportation System Joint Program Office, under which NASA, the FAA, DOD, the Department of Homeland Security, and the National Oceanographic and Atmospheric Administration would draft a plan incorporating the strategy, schedule, and resources needed to develop and deploy such a system. The reports of the American Society of Mechanical Engineers and the Aerospace Industries Association called for the creation of a new coordinating body, one that would oversee federal aeronautics research and development in general. The National Academies' Committee on Strategic Assessment of U.S. Aeronautics (1999) proposed an entity that, while similar, would reach beyond the federal government into industry and academia.

[36]National Research Council, Board on Science, Technology and Economic Policy, *Trends in Federal Support of Research and Graduate Education* (Washington, DC: National Academy Press, 2001). DOD accounted for 43 percent. Aeronautics is separated in the surveys from space or astronautical engineering research, in which NASA's dominance is, of course, even greater.

[37]See NASA, *The NASA Aeronautics Blueprint: Toward A Bold New Era of Aviation* (Washington, DC, 2002); and *Fiscal Year 2004 Strategic Plan* (Washington, DC, 2004).

And in the interest of safety and security, the NASA program is working on technologies ranging from blast-resistant luggage compartments and self-extinguishing fuels to an automated passenger information and threat assessment system.

According to independent evaluations as well as NASA reports, the agency's aeronautics R&D program has scored a number of significant technical successes, some of commercial importance. As recently as December 2004, NASA aeronautics successfully flew the first air breathing hypersonic vehicle, the X-43A. Moreover, despite declining resources that are discussed later in this chapter, the current program has been judged to have relatively high technical merit. The National Academies' 2003 evaluation of the program ranked over four-fifths of the 172 tasks under the vehicle systems program as either "world class" or "good" and only 17 percent as "marginal" or "poor." [38]

NASA's Management Challenges

NASA's accomplishments in aeronautics technology development are even more impressive in light of the many challenges faced by the program's managers, currently titled the Aeronautics Research Mission Directorate (ARMD).[39] The program's principal challenges include the following:

- ARMD has no institutional responsibility, resources, or capacity to directly implement technologies that the program develops except in unique prototypes or demonstration vehicles.[40] Rather, implementation in public or commercial systems is dependent on a host of other stakeholders: in the case of air vehicles, airframe and engine manufacturers and their component suppliers or, alternatively, military service procurement officials and defense contractors; in the case of environmental protection and noise reduction technologies, FAA regulators who mandate what steps need to be taken by commercial manufacturers; in the case of air traffic control systems, the operational arm of the FAA, including air traffic controllers and their union, the airlines, and airport operators; in the realm of safety and security, the Transportation Security Agency as well as the FAA and other parties.
- The intended users have exceedingly diverse goals, needs, time horizons, and levels of technical skill. Airframe and engine producers have high levels of technical capability, whereas other downstream institutions in the technology implementation chain, such as the FAA arm operating the nation's air traffic control system, have limited incentives and capacity to innovate. For operators of a highly complex system whose test is reliability,

[38]It is not indicated what proportion of the vehicle systems budget the low-ranked tasks represent.
[39]Previously known as the Aeronautics Enterprise, the program's scope, location, and workforce have remained largely the same through agency reorganizations and nomenclature changes, with the exception that responsibility for oversight of the Ames Research Center in northern California was shifted from ARMD to the Space Science Directorate in 2004. Ames continues to perform aeronautics R&D, mainly related to air traffic management, under ARMD's direction. Likewise, ARMD continues to have management responsibility for three other centers performing aeronautics R&D: Langley Research Center in Virginia, Glenn Research Center in Ohio, and Dryden Research Center, also in southern California. Before the transfer of Ames, ARMD had 40 percent of NASA's entire civil service complement.
[40]That would change if NASA aeronautics were to develop for the space program an airplane capable of planetary flight, an aspiration of the program but a distant prospect.

predictability, and above all safety, the introduction of new technology poses significant risks. Moreover, the culture of air traffic controllers is resistant to changes that reduce the element of human control.

- What users of NASA-developed technologies have in common, whether they are airframe or engine manufacturers or air traffic controllers, is that when new technologies become available or are mandated, they must be integrated into highly complex systems. ARMD does not have the luxury of developing discrete technologies that are readily implemented independent of other changes.
- ARMD supports a very broad spectrum of R&D activity and not merely along the continuum of basic through applied research, development, prototyping, and testing. Some arenas of activity—air traffic control and emissions and noise reduction are examples—are generally identified as public or quasi-public goods.[41] Were it not for NASA or some other public agency, little R&D would be performed and new technologies would not be developed because the benefits appropriable by private enterprise are too limited or too widely diffused to attract investment. In arenas of substantial commercial activity—engines and airframes and their components—a public investment may be appropriate because the research is too fundamental or the risk associated with the technology too great to attract investment. But for program managers it is more difficult to determine where to draw the line than it is when they are dealing with public goods that will otherwise be underfunded or ignored. In aviation, the difficulty has been compounded by the progressive concentration of the commercial aircraft assembly industry, down to a single domestic airframe producer and two commercial jet engine producers.[42] The fewer the competitors, the more problematic the government intervention.
- ARMD is responsible for three (and until recently, four) very large research centers with expensive, aging facilities and equipment and large contingents of civil service personnel. Having access to expertise and test facilities on a continuing basis is an asset to its mission in many respects and a sine qua non in some respects, but maintaining them consumes a large share of R&D resources and limits managers' flexibility.
- Finally, NASA aeronautics is overshadowed in resources, managerial attention, and political support by the agency's mission of space exploration and discovery. A fact of life since the creation of NASA, the discrepancies were if anything exacerbated by President Bush's announcement in 2004 of a costly, technically challenging mission to return human beings to the moon and eventually send them on to Mars.

Together these circumstances have set NASA aeronautics apart from most other federal R&D programs. Although many R&D programs are located in agencies with broader missions and must compete for resources with operational programs (for example, in the U.S. Department of Defense, DOD, the U.S. Department of Agriculture), the link between the R&D and the agency's principal mission is generally stronger than it is for aeronautics R&D in NASA. In some agencies the mission is focused on the support of fundamental research without concern for near-term application (NSF and the National Institutes of Health), but in others the agency has a

[41] A genuine public good is nonexcludable and nonrivalrous in consumption. Air traffic control is excludable. It may be nonrivalrous, but only until congestion occurs.
[42] At the same time, the component supplier base has grown and become internationalized and more competitive.

direct handle on implementation through procurement specifications (DOD) or regulation (EPA). Neither characteristic has applied to NASA aeronautics, although both do apply to the space program, encompassing both science and exploration. Perhaps the most clearly analogous programs in the federal portfolio are the Department of Energy's renewable and alternative fuels programs. They cover a broad spectrum of R&D, depend on private-sector users for implementation, support substantial research infrastructure, and have ranked relatively low among the parent department's priorities. Still, the alternative energy programs have at least one advantage over NASA's aeronautics. The prices of traditional fuels—oil, gas, and coal—make it relatively easier to distinguish which other technologies will draw private investment and which will not and to determine when a new technology is likely to be economically viable.

In light of these characteristics it is easy to see why concerns about implementation of NASA-developed aeronautics technologies recur regularly among NASA managers, customers, and observers. The challenge is not confined to effective techniques of handing off results to users but extends to careful selection and alignment of projects and skillful management of their progress.

NASA aeronautics has frequently been the object of proposals for organizational change to relieve some of the constraints and, presumably, facilitate innovation, primarily by giving managers of the program greater flexibility, especially in source selection and staffing of projects.[43] A core assumption of the recent public and private study commissions and panels is that aeronautics R&D activities are fragmented and would benefit from better cross-agency coordination, perhaps by a new organization. From time to time it is proposed more boldly to separate aeronautics from the space program or to raise its status and increase its independence within NASA. At our committee's workshop there was some support for the idea of divesting ARMD of the research centers and converting it into an external R&D program, much like DARPA, managed by a few highly creative scientists and engineers who support projects in academic institutions and private firms.[44] Another solution, favored by the President's 2004

[43]Reform proposals in federal aeronautics activities are not confined to NASA. In 1994 the Clinton administration proposed to reassign the air traffic control function of the FAA to a new government-owned corporation, the Air Traffic Services Corporation, financed by user fees and debt financing. It argued that air traffic control was best delivered by a "business-like" entity rather than the FAA command and control structure. U.S. Congress, Office of Technology Assessment, *Federal Research and Technology for Aviation.* OTA-ETI-610. (Washington, DC: U.S. Government Printing Office, September 1994), p. 7.

[44]The contrast between the DARPA model and the current ARMD configuration could hardly be greater. DARPA has an exceedingly lean management structure, with temporary personnel lacking job tenure but having considerable flexibility in negotiating arrangements with its external R&D performers. For example, DARPA makes liberal use of Other Transactions Authority, enabling managers to circumvent some traditional federal procurement constraints. In contrast, NASA maintains a large, fixed infrastructure of laboratories and other experimental facilities with civil service and contractor personnel. ARMD managers have less flexibility in deciding where work is to be performed and by whom and in working out collaborative arrangements. More fundamental, the customer bases of the two programs are also strikingly different. DARPA works for a small set of focused customers, the Office of the Secretary of Defense and military services, which not only support fundamental research but also have the resources and technical capacity to take promising technologies from relatively early levels of development to deployment in the field. ARMD has a diversity of customers inside and outside the government with different constraints, including, at least in some cases, limitations on their technical capacity and financial resources and conservative risk profiles with respect to both safety and financial risks. In many cases,

Commission on Implementation of United States Space Exploration Policy (the Aldridge Commission) is to convert the research centers into contractor-operated Federally Funded R&D Centers (FFRDCs).[45] This also received the support of some workshop participants as a way of introducing greater flexibility into the management of the NASA workforce.

Although all of these organizational changes could significantly affect the adoption and diffusion of NASA-developed technologies, our committee was neither asked nor constituted to evaluate any of these proposals in depth. Nevertheless, we observe that none of them would remove a fundamental challenge of aeronautics R&D management at NASA—namely, that the program is entirely dependent for its effectiveness on relations with diverse technology users outside NASA, putting many factors in the process of deploying new technology beyond the agency's control, regardless of its organization. Furthermore, reorganization does not address the fact that although the industrial and academic communities have argued repeatedly for a broad federal role in aeronautics R&D, these arguments have not translated into budget resources for NASA's program.

RESOURCES AND NATIONAL POLICY

The contrast between the case articulated by the private sector and the budget reality was dramatically underscored in 2005. At congressional request the National Aerospace Institute engaged more than 250 industrial representatives, academics, and other experts in a very detailed review of the NASA aeronautics R&D portfolio. Their April 2005 1,000-page report recommended a number of expanded and new initiatives over five years, amounting to an average annual budget increase of $888.5 million. In the meantime, the President's FY 2006 budget request of $852.3 million[46] represented a reduction of nearly $80 million from the actual funding level of $930 million for FY 2005. Furthermore, the budget projected a further drop in FY 2007 (to $727.6) and flat funding through FY 2010 ($717.6). Over the six-year period, in other words, the budget was expected to fall by one-quarter in nominal dollars (Table 1-1).

NASA's customers are averse to applying technologies unless their validation is well advanced or completed.

The committee does not prejudge whether a DARPA-like entity should or could be created to administer some elements of the aeronautics program, but the magnitude of the transformation should not be underestimated.

[45]This is the structure under which the Jet Propulsion Laboratory is operated for NASA by the California Institute of Technology. It combines government-owned contractor-operated (GOCO) and contractor-owned contractor-operated (COCO) features. By contrast, the other NASA research centers are entirely government-owned government-operated (GOGO) facilities, although heavily supported by on-site contract employees.

[46]*Budget Estimates, Fiscal Year 2006.* p. SAE 10-3. NASA represents the cut from FY 2005 as 6 percent, based on the FY 2005 Congressional Operating Plan, dated December 23, 2004, showing spending at $906.2 million. Using the FY 2005 appropriations for aeronautics, the drop is 8.3 percent from $930 million, as estimated by the American Association for the Advancement of Science.

TABLE 1-1 Administration Budget Request and Projections for NASA Aeronautics R&D, FY 2005-2010 ($ millions)

FY05 05 Budget	FY06 06 Budget	FY07 06 Budget	FY08 06 Budget	FY09 06 Budget	FY10 06 Budget
919.2	852.3	727.6	730.7	727.5	717.6

Source: *Budget Estimates, FY 2006*

The proposed FY 2006 budget simply continued a pattern. NASA's aeronautics R&D budget has been on a fairly steady decline since the late 1990s. Figure 1-1 illustrates the fact that that, at least through 2000, this is largely the result of progressively lower administration budget requests in constant dollars. Figure 1-2 shows the decline continuing through 2003.[47]

It is apparent to our committee that the private experts and stakeholders have not yet articulated a strategic vision for the federal role in aeronautics research and development that has gained the support of both the White House and Congress. In the past several years, nearly a dozen independent nonpartisan bodies have tried in both general and specific terms to make a case for a stabilized or increased NASA aeronautics budget, but all of them apparently have failed to impress the ultimate decision makers.

Former Associate Administrator for Aeronautics Research Victor Lebacqz may have put his finger on the problem in oral testimony to the House Science Committee in March 2005. He described two "distinct philosophies" for public investment in aeronautical research. On one hand, there are those who think aeronautics and aviation are a mature industry and market, one in which government's research role is best scaled back and left to private industry. This view holds that market forces will decide the nation's future as a commercial aeronautics power. On the other hand, there are those who think that there are many breakthroughs in aeronautics ahead, and they worry about the continuous large investments by foreign governments and competitors and the apparent shrinking market share of U.S. industry. This view holds that federal aeronautical investments are important for the nation's future military and economic security.

Dr. Lebacqz left no doubt which of the two philosophies of national investment in aeronautics most influenced the proposed budget for FY 2006: "This budget is consistent with the side of the policy issue . . . that says that the marketplace will in fact provide the best outcome."[48] He repeated appeals for a national dialogue aimed at reaching consensus on goals for aeronautics R&D. "If we have a national policy in aeronautics that says we will as a country invest in this area as one of our niche areas to maintain a competitive edge, then we will be able

[47]The discrepancy between the sets of figures in Table 1-1 (beginning at $919.2 million in 2005 and in Figure 1-1 (ending in 2003 at about $600 million) in part reflects a change in accounting for personnel, facilities, and overhead under the so-called full-cost accounting rule, adopted by NASA in FY 2001 to fully attribute these costs to programs. For this and other reasons it is difficult to construct accurate continuous budget charts. Not only did full cost accounting introduce a major discontinuity, but also budget categories, project titles, and bureaucratic organization charts have changed over this period. A recent RAND analysis of NASA external aerospace R&D spending, using data from the Federal Procurement Data System, showed a steady decline over the decade 1993-2003. Thor Hogan, Donna Fossum, Dana Johnson, and Lawrence Painter, *Scoping Aerospace: Tracking Federal Procurement and R&D Spending in One Aerospace Sector*. Santa Monica: RAND Corporation, 2005.
[48]Dr. J. Victor Lebacqz, oral testimony before the Subcommittee on Space and Aeronautics of the House Science Committee, U.S. House of Representatives, March 16, 2005 (recorded and transcribed by NRC committee staff).

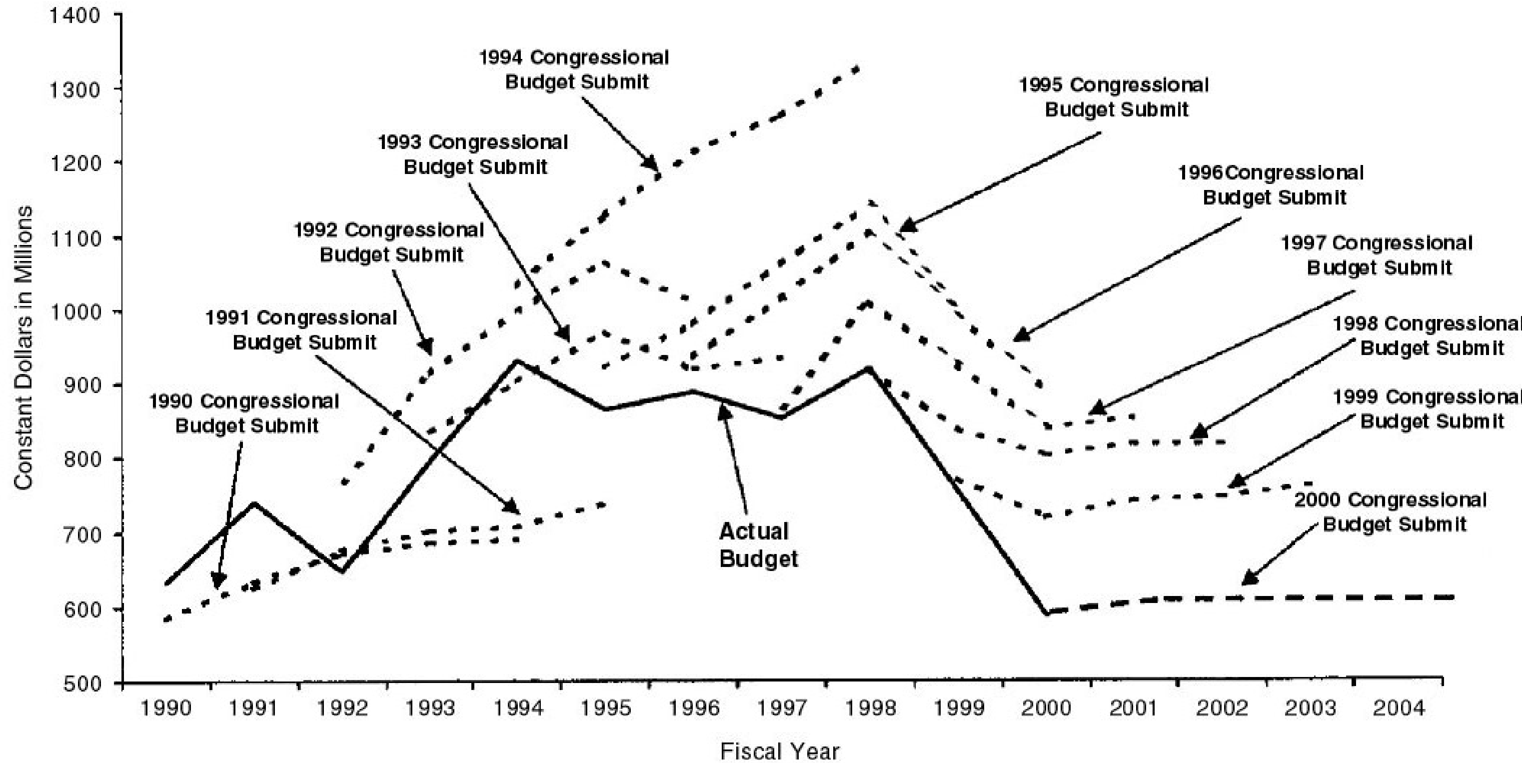

FIGURE 1-1 NASA aeronautics R&D budget requests and actual budgets, 1990-2000.
Source: NASA.

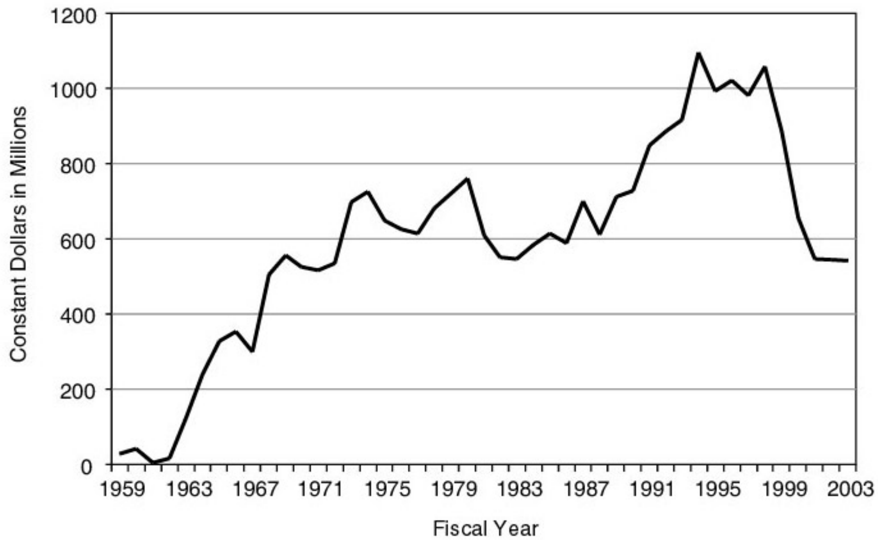

FIGURE 1-2 NASA aeronautics R&D budgets, 1959-2003 (constant 2002 dollars). Source: NASA.

to do that more clearly than we are now." Nevertheless, such a policy needs to be more nuanced than Dr. Lebacqz's dichotomy suggests. It needs to take into account the public good as well as industrial health objectives that NASA's aeronautics R&D involvement addresses.

<u>**Recommendation 1**</u>**: 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).**

PROGRAM FOCUS AND PRIORITIZATION

Even if NASA aeronautics program expenditures were stabilized, ARMD management faces severe constraints on its discretion. The first limitation, referred to earlier, is high "fixed" personnel costs. NASA cites $2.39 billion as the amount that the administration has requested for total agency employee salary and fringe benefits in FY 2006 and puts at 18,798 its total civil service workforce for the year. Based on these numbers, the average per employee cost across the agency for salary and fringe benefits is $127,141. As the total number of employees engaged in aeronautics R&D at the three research centers under ARMD's administration is estimated to be 2,059 in FY 2006, they account for about 30 percent ($261.8 million) of the aeronautics budget request.

Program Expenditures

As is apparent from Table 1-2, showing personnel employed at Dryden Flight Research Center (DFRC), Glenn Research Center (GRC), and Langley Research Center (LRC), a good deal of the FY 2005–FY 2006 budget reduction (91 percent or $61.28 million) was expected to come from the elimination of civil service positions—to be precise, 482 out of 2, 541 devoted to aeronautics research. By 2010 the civil service aeronautics workforce was projected to be less than half of its current size, the largest single-year reduction (573) being scheduled for FY 2007. Contractor positions were also slated to be cut between FY 2005 and FY 2010, although not quite as many in absolute numbers but about the same proportion nevertheless (47.5 percent). If the average burdened cost per in-house contractor employee is similar to that for civil service employees, contractor salaries and benefits at the research centers would amount to $142 million, pushing total expenditures for aeronautics workers (salaries and fringe benefits) slightly above $400 million in FY 2006, assuming the projected workforce reduction occurs.[49]

TABLE 1-2 Projected NASA Aeronautics Research Centers' Civil Service and Contractor Personnel, FY 2005-2010

Civil Service Employees	FY05 05 Budget	FY05 06 Budget	FY06 06 Budget	FY07 06 Budget	FY08 06 Budget	FY09 06 Budget	FY10 06 Budget
Aero DFRC	395	424	408	293	295	285	264
Aero GRC	861	790	647	429	404	385	362
Aero LRC	1205	1327	1004	764	690	647	604
Total Aero	2461	2541	2059	1486	1389	1317	1230

Contractor Employees	FY05 05 Budget	FY05 06 Budget	FY06 06 Budget	FY07 06 Budget	FY08 06 Budget	FY09 06 Budget	FY10 06 Budget
Aero DFRC	262	299	255	228	243	242	242
Aero GRC	480	295	267	235	233	230	216
Aero LRC	990	990	594	743	563	506	450
Total Aero	1732	1584	1116	1206	1039	978	908

DFRC = Dryden Flight Research Center, GRC = Glenn Research Center, LRC = Langley Research Center.
Source: *Budget Estimates, FY 2006.*

Two other components of the aeronautics research cost structure must be considered in assessing ARMD's decision latitude: general and administrative (G&A) expenses and congressionally directed research projects that might not otherwise be undertaken. Certain fixed administrative costs incurred by the agency arise from its responsibilities as defined in the Space Act, obligating NASA to maintain certain national facilities and core competencies in certain areas of aeronautics.

[49]With the appointment of a new NASA administrator in 2005, the reduction in workforce at the centers has been deferred.

G&A costs are normally determined for each center and applied as a percentage of labor cost involved in the program at that center. The center G&A costs at Dryden, Glenn, and Langley are high because of the obligation to support an aging legacy infrastructure. They range from 110 percent of direct labor costs at Glenn and Dryden to 144 percent at Langley, according to the budget submission. Optimistically, in FY 2006 this would leave only approximately $75 million out of the projected aeronautics budget for other programmatic costs, such as the extramural research program and the cost of subcontracts and demonstration costs.

A growing part of the extramural program is determined by Congress in directing funds to particular projects in the annual appropriations cycle. The number and cost of these projects has increased in recent years. Although in some instances there is little apparent relationship between the project and NASA's mission, some of the mandated expenditures reflect congressional views that some important public good objectives are being neglected in NASA's planned activities. Nevertheless the congressional prohibition on attaching administrative charges to the mandated projects amplifies the budgetary impact of the assignments, further constraining the aeronautics budget.

In previous years NASA has accommodated the budgetary reductions in a variety of ways, including closing some antiquated research facilities,[50] extending the timeline of certain projects, and ending certain projects at levels of development (in NASA parlance, technology readiness levels, or TRLs) earlier than originally planned. What has apparently not occurred, until it was proposed in the President's FY 2006 budget submission to Congress, is a commensurate reduction in ARMD's program scope or R&D portfolio.

Management of Technology

The tendency to spread resources over a wide range of opportunities to meet such diverse expectations as the NASA aeronautics program faces is understandable, especially when the technical merit of the activities is highly rated.[51] Still, the temptation needs to be resisted. One of the more robust findings of the management of technology (MOT) literature is that, over time, innovative organizations exhibit a rather sharply defined strategic focus. The pattern was perhaps first documented in the Japanese consumer electronics industry.[52] Later studies document a similar pattern in firms as diverse as Toshiba and Intel, Monsanto and Genentech, GE and IBM, and Corning and Motorola,[53] while extensive anecdotal evidence suggests an analogous force to

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[50]Testimony of Dr. Philip S. Anton, RAND Corporation, before the Subcommittee on Space and Aeronautics, House Committee on Science, U.S. House of Representatives, March 16, 2005, pp. 13-18, available at http://www.house.gov/science/hearings/space05/Mar16/Anton.pdf.

[51]*Review of NASA's Aerospace Technology Enterprise*, p. 16.

[52]See especially Richard S. Rosenbloom and William J. Abernathy, "The Climate for Innovation in Industry: The Role of Management Attitudes and Practices in Consumer Electronics," *Research Policy* 11 (1982), pp. 209-225; and Rosenbloom and Michael A. Cusumano, "Technological Pioneering and Competitive Advantage: The Birth of the VCR Industry," in Michael L. Tushman and William L. Moore, eds., *Readings in the Management of Innovation, 2nd ed*. (Cambridge, MA: Ballinger, 1988).

[53]See M. Maidique and R. Hayes, "The Art of High Technology Management," *Sloan Management Review* 25 (Winter 1984); J. Morone, *Winning in High-Tech Markets* (Boston: Harvard Business School Press, 1993); P.A. Abetti, U. Sumita, and Y. Kimura, "Toshiba Information Systems—From Mainframes to Laptops and Notebook Computers," *International Journal of Technology Management, Special Issue* (1995), pp. 139-160; G. Lynn, J. Morone, and A. Paulson, "Marketing and Discontinuous Innovation: The Probe and Learn Process," *California Management Review* 38 (3, Spring 1996).

be at work in such historically innovative firms as 3M, Oracle, Cisco, Microsoft, Fanuc, and Canon. Evidence of the impact of strategic focus on innovativeness over time can also be found in a recent, multiyear, multifirm study of the management of radical innovation.[54]

In these and many other cases, a well-defined, explicitly articulated strategic focus powerfully shapes the entire context for technology management. This strategic focus serves as a guide for distinguishing opportunities that are important, even vital, to pursue from those that are merely interesting. In addition, it fuels persistence in the pursuit of those opportunities. Most major industrial innovations require a decade or more of development, during which they inevitably encounter delays, setbacks, and failures. It is only if these projects can be justified as strategically central that they garner the continuing support necessary for their long, often tumultuous development.

Furthermore, over time, a sustained strategic focus, accompanied by sustained technology development in support of that focus, fuels the development of unique capabilities in the firm's domain of concentration. As its technology and marketing organizations focus on the same general domain through successes, partial successes, and failures, they learn ever more about the technology and markets in that domain; they also accumulate ever more expertise and talent, a situation that in turn increases the odds of successful innovation in that domain. Thus, the history of technological innovation in the most highly innovative firms appears in hindsight to consist of a succession of development projects—some successful, some partially successful, some unsuccessful—with each project building on its predecessor and all projects exploring promising opportunities within the firm's strategic focus.[55]

Although innovative firms demonstrate a striking pattern of technology push, that push evolves within a widely shared strategic framework that guides effort in certain directions and not others. In contrast, firms that lack strategic clarity tend to bounce from one opportunity to another, never focusing on a domain of opportunity long enough to fully explore its possibilities or build the competence necessary to exploit them.[56]

Effects on Innovation

The constraints on NASA's aeronautics program budget have direct and indirect bearings on innovation. First, in the absence of an effort to adjust the R&D portfolio to available resources by foregoing projects that may have technical promise and support but are not affordable, the inclination will be to extend project timelines. In NASA this practice is said by NASA managers and customers to be fairly common (see Chapter 2). In an innovation-oriented organization, ingredients for success start with clear expectations and commitments and

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[54]R. Leifer, C. McDermott, G. O'Connor, L. Peters, M. Rice, and R. Veryzer, *Radical Innovation* (Boston: Harvard Business School Press, 2000).
[55]For example, after its successful development of the CT imaging business, GE Medical came to view itself as being in the business of diagnostic imaging, whereas it had previously considered itself to be a more general medical equipment enterprise. It then explored in ambitious fashion, over a two-decade period, development of digital X-ray (a failure), nuclear imaging (a modest success), ultrasound (another failure), MRI (a huge success), and again digital X-ray (a success). The same pattern was exhibited by Corning from the mid-1970s to the early 1990s (cellular ceramics, optical fibers, LCD glass, glass-plastic composites) and by Motorola from the late 1940s through the 1980s (mobile radio, portable radio, paging, cellular telephones, portable data, iridium). See Morone, *Winning in High Tech Markets*.
[56]The classic example is the American consumer electronics industry. See Rosenbloom and Abernathy, "The Climate for Innovation in Industry."

accountability for meeting those commitments on a planned schedule, so that both leadership and development teams are on the same page throughout the project cycle.

A second tendency is to declare projects completed earlier in the development of new technologies than originally planned or earlier than ideal from the standpoint of either persuading or enabling users to take them up. Several participants in the committee's workshops expressed the concern that too many NASA aeronautics projects stopped short of full demonstration of their technical success and utility to users. Experience shows that a potential innovation must be reduced to practice in the complex environment in which it will function before it will be accepted as credible and adopted by the target user community. Such demonstrations in aeronautics often require large expenditures, as has been amply demonstrated by prior NASA and DOD advanced technology demonstrations. The costs of such demonstration programs normally amount to hundreds of millions of dollars. A major part of these demonstration costs is attributable to the systems phenomenon described earlier—unless the technology can be shown to perform as part of the highly integrated system in which it will be used, the prospective user community is likely to discount it.

Quite apart from concrete budget limitations, it is apparent that NASA aeronautics program managers feel under increasing pressure to favor shorter term, nearer payoff development projects. As in other federal agencies, the Office of Management and Budget (OMB) is seen as a primary source of this pressure. In our interviews at the research centers, NASA informants cited a reluctance to carry research to higher levels of technology readiness out of concern that OMB would perceive such an activity as inappropriately close to market needs and that NASA's private-sector customers should be responding to this need on their own, without substantial government support.

A third impact of sharply declining budgets is on core technical competencies. Insufficient attention to core competencies was a concern of the National Academies' 2004 Review of NASA's Aerospace Technology Enterprise, which concluded that the Vehicle Systems Program (VSP) in particular reflected lack of a "good understanding of the core competencies (in order of importance) required to meet [the] goals" set forth in its mission statement. Similarly, the panel judged the VSP investment strategy to be ad hoc, characterizing it as having "too many unprioritized projects and tasks and no apparent methodology to determine which research areas will provide the greatest benefit to the U.S. gross domestic product and do the most public good."[57]

Aviation Safety and Airspace Systems Programs

The previous National Academies' panel appears to ascribe this lack of clarity at the VSP to an overall failure by NASA to maintain a firm grip on the relative value of its many capabilities. This may have been of less moment when the agency's prowess and resources were unrivaled. The competencies developed by NASA during the 1960s, 1970s, and 1980s, the panel recalled, "enabled the U.S. aerospace industry to take a dominant position in both the military and commercial marketplaces worldwide." Today, however, when industry state of the art has overtaken NASA capabilities in some areas, the fact that "NASA no longer has a clear set of core competencies and technologies" carries a substantial price. Because "NASA has not reduced the

[57]Representatives of the committee were told in January 2005 that NASA had begun an agency-wide inventory of core competencies—but also that this activity did not begin with aeronautics research and appeared unlikely to reach it for some time.

scope of [its existing] core competencies or research focus areas even in the face of changing market needs and reduced budgets," some of its research activities—here, the panel was referring specifically to those within the VSP—"find themselves on budgetary 'life support.'"[58]

The panels that reviewed the two other programs under aeronautics research, the Aviation Safety Program (AvSP)[59] and the Airspace Systems Program (ASP), for the same report did not address these concerns with the same degree of explicitness. Still, comments included in their reports exhibit comparable misgivings about the efficacy with which these programs were managing both their core competencies and the projects to which these competencies were applied.

The former panel asserted that "there were too few in-house personnel and that too much of the research was being conducted by contractors" in the case of some tasks of the then-AvSP, adding that such distribution "tends to weaken the core competencies of NASA."[60] Moreover, it explained that each individual task within the AvSP is structured to last five years, making it "difficult, if not impossible, for NASA to maintain core competencies with these five-year program cycles." Describing these short cycles as "more suitable for a product-oriented program,"[61] it raised a question about the balance between fundamental and product-driven research[62] within the then-AvSP, having found several instances of products being developed by NASA that are similar to or have considerable overlap with products developed by industry. It therefore recommended that the program "compare (benchmark) its research projects against those of other research and development entities in government and industry to ensure that NASA's work is leading,"[63] adding: "NASA should not be working in a specific technical area unless it is leading the field."[64] This appears particularly important in the light of evidence that in some instances the breadth of the work being done was at the expense of technical depth.[65] The ASP panel expressed similar concern that ASP research was generally too focused on short-term, incremental payoff work, whereas it should instead support basic research relevant to long-term objectives and focus on areas of greatest payoff—that is, areas that relieve choke points and other constraints to a more efficient air transportation system.[66]

A fourth concern from an innovation standpoint is the impact of shrinking budgets on the external R&D program. Any vibrant, innovative R&D program should seek and support ideas outside its organization. Funds should be available for maintaining an extramural program that would facilitate contact with significant numbers of innovative participants from academia and industry.

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[58] *Review of NASA's Aerospace Technology Enterprise*, p. 13.
[59] This program, subsequently renamed, is now known as the Aviation Safety and Security Program (AvSSP).
[60] *Review of NASA's Aerospace Technology Enterprise*, p. 76.
[61] *Review of NASA's Aerospace Technology Enterprise*, p. 74.
[62] *Review of NASA's Aerospace Technology Enterprise*, p. 73.
[63] *Review of NASA's Aerospace Technology Enterprise*, p. 76.
[64] *Review of NASA's Aerospace Technology Enterprise*, p. 4.
[65] *Review of NASA's Aerospace Technology Enterprise*, p. 78.
[66] A cause of this short-term focus, the panel suggested, is that NASA "tends to view success in terms of the ability to mature technology and get the FAA to implement it for operational use." Attributing to "[s]ome FAA users" the opinion that "this view of success leads NASA to focus too much on implementation issues, which NASA may not be qualified to address given its limited operational experience," the panel declared: "Success of NASA applied research tasks should not be defined solely in terms of implementation." *Review of NASA's Aerospace Technology Enterprise*, pp. 3-4.

In short, ARMD faces a dilemma often confronting private-sector managers of technology: opportunities for new technology development exceed the resources available, especially once work progresses beyond the stage of preliminary exploration. In those circumstances, the principal task of managers is to distinguish between opportunities that are worth pursuing and affordable and those that, however attractive and technically promising, must be forgone. Deciding which pathways to forgo lies at the heart of competent technology management, and it is essential to achieving the objective of innovation. Instead, NASA has spread resources across more R&D endeavors than can be sustained to the point that users are able to take up the results. The committee thinks that unless NASA aeronautics R&D managers narrow their mission focus and align programs with available resources, the advice we offer with respect to management techniques to facilitate innovation will be largely ineffectual.

<u>Recommendation 2</u>: 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.

Prioritization of the Vehicle Systems Program

Last year, there was a short-lived effort in this direction. In connection with a sharp $109.5 million (20 percent) drop in the FY 2006 budget request for the Vehicle Systems Program, NASA announced a striking change in scope of activity. ARMD would "transform its program to focus on projects that demonstrate breakthrough technologies/capabilities," changing from a "philosophy of broad technology based research and technology to a few focused projects for development and demonstrations of barrier breaking technologies, reducing the number of high-risk, high-payoff demonstrations, and [eliminating] incremental aeronautics technology projects" that merit "a federal role."[67] Specifically, the focus would be reduced to achieving flight demonstrations in four areas of subsonic noise reduction, sonic boom mitigation, zero emissions, and high altitude, long-endurance UAVs or remotely operated aircraft. ARMD would greatly reduce or abandon altogether work on conventional subsonic aircraft technology, including aerodynamics, smart structures, and rotorcraft.[68]

Our committee did not address the technical merits of ARMD's four remaining "breakthrough" projects in vehicle systems development. Instead, we considered whether this descoping action, although perhaps a psychological breakthrough of sorts,[69] represents the kind of focusing and selection process that we think is vital in ARMD's current circumstances.

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[67] *Budget Estimates,* p. SAE 11-5.
[68] *Budget Estimates,* p. SAE 11-15. The National Academies' report, *Review of NASA's Aerospace Technology Enterprise,* lamented the last prospect, saying that "research in civil applications of rotorcraft will not be conducted elsewhere in government or industry and . . . NASA's decision to discontinue rotorcraft research has left critical civilian needs unaddressed" (p. 8).
[69] In its briefing to the House of Representatives Appropriations Committee staff, NASA described the VSP revision as a "landmark opportunity" to take a "new approach" that could serve as a "pilot for

First, it is not clear to us, although we do not rule it out, that a strategy of how to address certain national needs guided the selection of program emphases. The articulated rationale for the choice of the areas of subsonic noise reduction, sonic boom mitigation, zero emissions aircraft, and high-altitude, long-flying UAVs is that they could demonstrate a series of technical successes or "breakthrough technologies/capabilities" within a few years and periodically thereafter, in contrast with the previous philosophy of broad technology-based research and technology or a "field of 1,000 flowers approach."[70] There is a pronounced public good rather than a commercial or precommercial character to the projects selected (UAVs being of principal interest to the military and the weather service), but this is not explicit. ARMD's mission statement in the FY 2006 budget submission continued to emphasize its general contributions to an efficient air transportation system, as well as developing new uses for science or commercial applications as well as to improving aircraft performance.[71]

A second, related concern is that the downsizing was budget crisis–driven rather than an effort to right-size the budget to a set of strategic priorities. Unless the new focus has a compelling, articulated rationale, it remains vulnerable to further budget cuts rather than strengthening the program and its support, especially in the event that technical success is more elusive or longer term than planned. In a "Risk Management" discussion accompanying the FY 2006 budget submission, NASA actually conceded that elements of its remaining research portfolio might become imperiled:

- "RISK: Given significant cost overrun/schedule slip in a project deliverable, there is the possibility that lower priority activities may be descoped or eliminated . . . .
- "RISK: Given that technologies from other programs do not meet planned readiness levels, there is the possibility that this program's cost and schedule may be impacted . . . .
- "RISK: Given customer needs and requirement changes, there is the possibility that the 15-year roadmap [to be delivered in fall 2005, according to Dr. Lebacqz[72]] will need to be updated."

To mitigate each of these risks, ARMD promised to "track progress . . . and maintain contingency plans, including further descope options."[73]

Third, because the transformation was a part of a closed-door budget process of negotiation exclusively between NASA and the White House, it proceeded largely without consultation with users and customers, both those who might be expected to benefit from the new priorities and those who might be disadvantaged by the downgrading or elimination of other activities. ARMD officials conceded as much, stating in the budget request, "Over the next year, the [Vehicle Systems] program will work with the aeronautics community to define the

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transforming all" activities under its purview. NASA briefing of the staff of the House of Representatives Committee on Appropriations, March 8, 2005.

[70]NASA briefing of the staff of the House of Representatives Committee on Appropriations, March 8, 2005.

[71]*Budget Estimates, Fiscal Year 2006,* p. SAE 10-3.

[72]Statement of Dr. J. Victor Lebacqz, associate administrator for aeronautics research, National Aeronautics and Space Administration, before the Subcommittee on Space and Aeronautics, Committee on Science, U.S. House of Representatives, March 16, 2005, p. 3.

[73]*Budget Estimates, Fiscal Year 2006*, National Aeronautics and Space Administration, p. SAE 11-16.

scope of the overall program,"[74] scheduling workshops *after* the budget announcement to explain the action and seek reactions to it, for example, from the aircraft and engine manufacturers. As we describe in the next chapter, this after-the-fact consultation with technology users is the reverse of the process the committee thinks is critical for innovation.

In the end, both a new NASA administrator and congressional authorizing and appropriating committees turned aside the VSP revision and restored the status quo, including the budget level, underscoring our overriding concern that a national policy, a strategic agency focus, and a set of program priorities need to be articulated and agreed on. This process needs to involve ARMD management, but it exceeds the grasp even of NASA's leadership. It needs to begin at the highest levels of government, with the White House and Congress.

[74] *Budget Estimates, Fiscal Year 2006,* p. SAE 11-14.

2

Innovation Facilitators and Accelerators for Aeronautics

The lack of clarity about the purpose and priority of the NASA aeronautics program has made it difficult for the committee to comply with our charge—to recommend practical measures to enhance the implementation of NASA-developed technology in the Aeronautics Research Mission Directorate (ARMD). Obviously, the advice would not be the same for projects designed to yield fundamental knowledge of aerodynamics or materials or human factors and projects undertaken for clearly identified customers leading to prototype technologies, for example for fuel-efficient commercial aircraft engines or advanced air traffic control systems. If the former were to constitute the core of the NASA program, then our focus should be on how well fundamental knowledge is disseminated to all potential users, for example, via peer-reviewed publication, the participation of investigators in scientific and technical meetings, and training of entrants into the professional workforce. We focused instead on NASA's efforts to develop solutions targeted to specific users' needs and the efforts made to get the solutions adopted. Our focus on innovation in this sense led us to examine the management of the R&D process and the hand-off of resulting technologies.

In our view, refocusing the NASA aeronautics program exclusively on fundamental research is neither a likely nor a very desirable result of the policy deliberations so clearly needed. The public good areas of NASA R&D work in which the argument for government involvement is strongest—safe, efficient air traffic management and environmentally benign aviation operations—are arguably the areas in which users need fairly well-proven technologies to be delivered and in which NASA's technical capabilities are in some respects superior. In all likelihood, ARMD will continue to have a portfolio quite diversified in terms of the stage of technology development being pursued. If it does not, the program could rather quickly lose its relevance and much of its support. That, in any case, is our premise. We further assume progress in articulating a mission reflecting financial realities, stakeholder needs, and NASA personnel and contractor capabilities and research infrastructure.

In this chapter we consider a variety of decision-making processes, tools, and incentive structures that will aid the process and enhance the prospects of innovation in the remaining portfolio. These include cohesive portfolio planning, engagement of stakeholders in the prioritization process, preidentifying the stages of and criteria for resource allocation and project continuation or termination decisions ("decision gates"), and planning for technology transitioning. In addition, we outline a number of personnel and financial management practices that can contribute to innovation.

Those tools might broadly be conceived as process discipline. Fundamental to keeping an organization on a path of relevant accomplishment is a set of tools that accelerate decision making. Quite the opposite of constraining an organization in bureaucracy, process tools and discipline help accelerate results and aid in decision making by clarifying expectations among customers, leadership, and development teams. These tools provide an expectation that mechanisms and metrics need to be developed to keep innovation relevant in terms of the values it can provide. These tools also help clarify schedules and timelines. Notions that innovation cannot be scheduled, that invention has to happen on its own pace, contribute to ignoring customer needs and, on the part of the innovator, diminished expectations of creating value.

In recommending these tools, the committee recognizes that there are important differences between public agencies and private firms, for example in their ability to focus resources narrowly, to reallocate funds, and to change or transfer personnel. We do not thoughtlessly recommend practices that are appropriate solely for private firms but are inappropriate and impossible for ARMD to implement. In fact, a number of the practices that we think NASA should consider are ones that derive from public-sector experience, including that of NASA.

At the same time, the composition of our committee does not reflect sufficiently broad NASA experience to anticipate all of the challenges that might arise in implementing our recommendations. We do recognize that objectives requiring negotiation with the Office of Management and Budget (OMB) or congressional authorizing and appropriating committees (or both) are likely to be harder to achieve and require more accommodation than measures within NASA's current authority, but even in the latter case, some of our proposals may be at odds with traditional practices that are difficult to change. The recommendations are not intended to represent a package that must be accepted as a whole.

PORTFOLIO APPROACH AND COHERENT ALIGNMENT WITH MISSION AND CUSTOMERS

Although the strategic focus discussed in Chapter 1 is the single leading principle of best-practice R&D management, a close second is to

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

Individual R&D activities should not operate independent of an overall understanding and agreement of how they contribute to and fit within the portfolio.[1] Key dimensions of the portfolio include balance across goals, timeframe, level of risk and potential value, and skill sets.

Another key dimension that should be explicit in developing the portfolio is the national additive value, that is, the degree to which ARMD is uniquely suited to pursue the R&D "as only NASA can." Easy to say, yet difficult to identify. ARMD should focus on where it is not competing or duplicating what is or could be done in industry, universities, the Department of

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[1]Philips, for example, one of the world's leading consumer electronics firms, calls its portfolio of R&D activities a "program haystack," with cross-portfolio analysis of each program or research competency's horizontal and vertical contributions to other programs or competency areas. Vertical research programs, such as health care systems, directly target specific customers and product areas. Competency areas, such as devices and micro-systems, encompass broadly applicable technology components that support across the program silos horizontally. This allows Philips to view different R&D investments and make decisions across and among the different silos. See Dominic Busher et al., *Management of Technology in Europe 2003: Comparing Strategies and Tools in 17 High Technology Organizations*, Todd A. Watkins, contributing ed. (Minneapolis: National Technological University, May 2003), p. 16. Available at http://www.lehigh.edu/~taw4/eumot03.pdf.

Defense (DOD), or other agencies. In pruning the portfolio, this should be a primary guiding principle.

Many useful portfolio assessment and planning tools exist (graphical representations like risk-reward bubble diagrams, technology roadmapping and milestones, future scenario visioning, stages and gates reviews, strengths-weaknesses analysis, cost-benefit-risk assessment, etc.), developed by a growing industry of consultants, textbooks, and how-to primers.[2] Our committee's collective experience suggests that

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.

We emphasize that what is important is not the specific tools employed—organizational idiosyncrasies suggest that no single set of tools will work in all contexts—but that the decision-making system is transparent, designed and understood by those who will implement it. The process should not be overly complex or burdensome; straightforward tools exist. The hard but most valuable part is not the tools or information gathering associated with them but the quality and depth of the conversations they can facilitate.

Best practice also means rigorous pruning of portfolio elements found to be yielding limited value. Hence, ARMD should

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.

In the committee's second workshop, David Whelan, a Boeing and former senior manager at the Defense Advanced Research Projects Agency (DARPA), described the notion as midterm exams for projects, deciding what should be required to pass. Decision gates and specific targets set criteria for hand-off from one phase to the next, including the hand-off to the user. Best practice also assesses and ensures that the technology readiness needed by the customer is understood and met by the developers. Key elements include sunset provisions and criteria for retiring projects. Terminating projects that fail midterms also increases economic flexibility to more rapidly pursue new opportunities. The process requires knowledgeable, disciplined leaders to operate effectively.

We heard repeatedly in our interviews and at our workshops that there are several impediments to successful R&D portfolio management at ARMD apart from lack of mission

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[2]Some leading books include P.K.S. Rousel and T. Erickson, *Third Generation R&D: Managing the Link to Corporate Strategy* (Boston: Harvard Business School Press, 1991); and R.G. Cooper, S.J. Edgett, and E.J. Kleinschmidt, *Portfolio Management for New Products, 2nd ed*. (Reading, MA: Perseus Books, 2001). Shorter articles include N. Danila, "Strategic Evaluation and Selection of R&D Projects," *R&D Management* 19(1, 1989), pp. 47-62; P. Groenveld, "Roadmapping Integrates Business and Technology," *Research Technology Management* (September 1997), pp. 48-55,; D.L. Hall and A. Nauda, "An Interactive Approach for Selecting IR&D Projects," *IEEE Transactions on Engineering Management* 37(May 1990).

clarity around which to build a portfolio. First, ARMD and NASA research activities more generally have been "projectized" and decision making done largely top-down in silos isolated to a degree that we think runs counter to R&D portfolio best practices. Each project manager and the upper layers of administration should understand how each project fits within the broader portfolio and how it contributes to the overall focused strategy and to external stakeholder needs. We concluded that ARMD's managerial approach does not fully meet this test. One NASA project manager, speaking about silos in a single NASA center, described it this way: "I look out the window here and see all these ostriches in separate sandboxes, not looking up to know what's going on around in other sandboxes, or understanding why they are doing what, or how their activities connect with the customer." Similarly, John Klineberg, chair of a National Academies study assessing NASA's aeronautics technology programs, speaking before Congress in March 2005, testified that "subproject and task-level plans, funding, goals, metrics, staffing, and responsibility are often difficult to define or cannot be clearly traced back to a plan or vision for the program as a whole."[3]

The organizational and geographic separation of the three major ARMD facilities magnifies the silo problem. For example, our interviews with technology managers at the Ames Research Center led us to believe that work on air traffic management there is not closely linked to related work at the Langley Research Center. The groups appeared not to be thoroughly familiar with each others' work or how their activities relate to one another. This is a clear sign that portfolio planning is not well established in ARMD. That said, one positive sign is that at the time of our visits the two groups were planning to meet in the near future to identify ways to leverage each others' activities.

Second, best practice suggests there should be more coherence and organizational agreement about the balance across various dimensions of the portfolio. In our interviews, some ARMD mangers reported that they perceive themselves under great pressure, mostly from OMB, toward shorter term, nearer payoff development projects—"we need successes to justify our budgets." And "long-term kinds of things seem consistently difficult to keep," as they are "always the first thing to go when there are budget issues at almost all levels." Some blue-ribbon external review committees agree that ARMD sometimes does not take its technologies far enough toward implementation. In contrast, other managers believe and some external reviews[4] and political pressure against perceived corporate welfare suggest the opposite, that government-funded laboratories should focus more on long-term fundamental science and high-risk, high-payoff breakthroughs.

This kind of disagreement, this lack of coherence among the views of various managers in the organization as to what the research organization is or should be doing, is to us a signal that technology management best practices are not well established. The individual projectized parts do not add up to a cohesive whole nor do they have a common understanding of their collective purpose.

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[3]Statement of Dr. John M. Klineberg, Chair, Committee to Review NASA's Aeronautics Technology Program Aeronautics, and Space Engineering Board Division on Engineering and Physical Sciences, National Research Council, the National Academies, before the Committee on Science Subcommittee on Space and Aeronautics, U.S. House of Representatives, March 16, 2005. Available at http://www.house.gov/science/hearings/space05/Mar16/Klineberg.pdf.
[4]E.g., National Research Council, *Review of NASA's Aerospace Technology Enterprise: An Assessment of NASA's Aeronautics Technology Programs* (Washington, DC: The National Academies Press, 2004).

R&D portfolio management best practice is to avoid exclusive focus one way or the other but rather achieve a balance across long-, medium-, and short-term R&D. Along these lines, a 2003 national steering committee on aeronautics and aviation technologies, organized by the Office of Science and Technology Policy and sponsored by the American Society of Mechanical Engineers, suggested and we agree that NASA aeronautics should

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."[5]

Criteria for including or eliminating R&D activities should be driven by the focused mission and key stakeholder needs. We discuss the importance of engaging stakeholders in more detail below. A potential bonus of a balanced approach would be political: near-term successes could help defend longer term programs' budget lines. The perceived public value of ARMD research would be clearer than with entirely long-term breakthrough programs.

We also heard multiple reports of a third significant impediment to R&D portfolio best practices, a reluctance to terminate projects Indeed, the incentive structure works strongly against it. Terminating projects does not quickly save resources because legislation makes it difficult or impossible for ARMD managers independently to move resources or reduce civil service staff quickly. This structural inability limits incentives to prune and to make midcourse corrections. We address staffing flexibility in more detail below.

One indication of the prevalence of this tendency is that it has an internal nickname: "slip and dip." This refers to the pressure to first oversell a project's potential to attract funding in the annual political cycles and then to stretch goals and timelines as budgets allow. One former ARMD manager put it bluntly: "Aeronautics has to make promises it knows it can't meet in order to get funding. . . . A lot of times we stretch ourselves more than we think we should, to sell the program. Otherwise, we won't have anything." A second manager referred to "the hollowing out of milestones. . . . [I]t's not that clear to me that there's a penalty for not delivering." He explained that project managers put most milestones in September, just before the end of the fiscal year. "You deliver something less but like what you promised, and unless you've wasted money or done something stupid, they give you another crack at it."

John Klineberg similarly noted, in the context of artificial five-year sunset provisions on research programs, that some longer term research had been disguised as a series of five-year plans under different names and different organizational structures.[6] Such artificial timelines are budget driven, rather than technology and challenge driven. Unfortunately for innovation management, one- and five-year timelines do not fit all technologies. The result is that the time horizons of ARMD technology problems are not in line with pressures of external bodies and contingencies well beyond ARMD management's control. This makes efficiently planning and managing the resources and gauging technical progress remarkably difficult.

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[5]American Society of Mechanical Engineers, Aerospace Division, *Persistent and Critical Issues in the Nation's Aviation and Aeronautics Enterprise*, (Washington, DC, November 2003).
[6]Statement of Dr. John M. Klineberg, Chair, Committee to Review NASA's Aeronautics Technology Program Aeronautics, and Space Engineering Board Division on Engineering and Physical Sciences, National Research Council, the National Academies, before the Committee on Science Subcommittee on Space and Aeronautics, U.S. House of Representatives, March 16, 2005.

An associated tendency we noted among ARMD managers is to see all projects as worthy. Clearly, the vast majority of ARMD activities do have value. Indeed, recent NRC reviews found few obvious weak projects from a technical point of view.[7] But the relevant managerial criterion cannot be whether individual projects have absolute value but rather prioritizing their value relative to each other in the context of severely constrained and shrinking resources. Pursuing large numbers of hollow, isolated projects aimed exclusively at short-term results is characteristic of worst practice, not best.

This tendency continues even under the refocused new FY 2006 budget proposals. Of the 11 projects in the proposed FY 2006-FY 2010 Airspace Systems Program schedule, 9 have milestone slips of at least a year, including several that also "descope" (the dip). A tenth dips without extending the milestone. Only the eleventh is scheduled for cancellation. Organization-wide application of portfolio assessment and uniform decision-gate processes would foster the conversations needed to enable cross-project evaluation.

A fourth major impediment to R&D portfolio planning at ARMD is the growth in congressional directly funded projects. At NASA as a whole, these projects increased from $74 million for six items in FY 1997 to $426 million for 167 items in FY 2005.[8] This 28-fold increase in the number of projects and 5-fold increase in costs had to be funded by offsetting reductions in ongoing NASA programs. The FY 2005 NASA earmarks in aeronautics amounted to $92 million. Compare this to the entire budget for air traffic management research, the Airspace Systems Program for that same year: $152 million. Indeed, fully 14 percent of the ASP budget was congressionally earmarked. Given fixed facility infrastructure costs and civil service employment constraints, this means that a significant fraction of ARMD's portfolio is largely beyond managerial control. To make matters more difficult, NASA is prohibited by Congress from charging administrative expense overhead to these projects, in contrast to the full cost accounting principle applied to other programs.

Earmarks can reflect a congressional perception that NASA officials are neglecting an important component of their program. For example, funds were increased for rotorcraft development following NASA's elimination of this program. However, as is frequently the case, the rotorcraft funding mandate came without a corresponding increase in the aeronautics budget and forced a reduction in some other programs, playing havoc with the budget planning process. Increased stakeholder participation in portfolio planning and budget balancing can help contain earmarking motivated by disagreement with NASA's priorities. But in some instances, earmarks are indicative of a philosophical conflict over whether a market failure exists to justify government intervention to support R&D. Earmarks are also used to appeal to local constituent interests. No budget planning process can eliminate earmarks in these circumstances.

Although this practice is unlikely to cease or even significantly decline, there are steps that ARMD can take to limit its disruptive effects. One constructive action along these lines was a suggestion by former NASA administrator Sean O'Keefe to the Senate Appropriations Subcommittee that NASA would begin to subject earmarks to selection criteria applied to all nonsolicited, noncompetitive proposals. These criteria include "relevance to NASA mission, intrinsic merit and cost realism."[9] NASA management is well aware of the problem and the

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[7] *Review of NASA's Aerospace Technology Enterprise*.
[8] NASA FY05 Initial Operating Plan. Available at http://www.nasa.gov/pdf/107781main_FY_05_op_plan.pdf.
[9] NASA FY05 Initial Operating Plan. Available at http://www.nasa.gov/pdf/107781main_FY_05_op_plan.pdf.

technical disruptions they cause. We discuss below financial management options for handling externally mandated projects.

There are some promising examples of the use of portfolio planning tools in various parts of ARMD and evidence that these tools can in fact be successfully implemented. We note, for example, that NASA participated in technology roadmapping working with the Federal Aviation Administration (FAA) in developing the FAA Operational Evolutionary Plan.[10] We also understand that a NASA-wide core competency review and prioritization was under way in 2005. We noted earlier a problem with core competency understanding in the Vehicle Systems Program (VSP). These are good signs but appear to us as ad hoc, rather than parts of a systematic organization-wide practice of portfolio analysis and planning. For example, we are troubled that managers at Langley perceived that the review primarily focused on supporting space exploration, not aeronautics.

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.

In this context, we also encourage expanded NASA-wide use of skills assessment tools, such as information technology systems, to collect and sort the status of all education, experience, and skills throughout the organization, so that the right people can be flexibly assigned high-priority tasks anywhere in the organization. This can be especially valuable in accelerating schedules in early innovation phases.

ARMD has also succeeded in some pruning in response to falling resources. External reviewers suggest that the result has been a reasonably internally balanced portfolio-like outcome. A 2004 RAND Corporation study of wind tunnel and propulsion-test facilities concluded that "currently, redundancy is minimal across NASA. Facility closures in the past decade have eliminated almost a third of the agency's test facilities in the categories under review in this study. In nearly all test categories, NASA has a single facility that serves the general- or special-purpose testing needs, although some primary facilities also provide secondary capabilities in other test categories." [11] For the overall portfolio, it found "the test complex within NASA is mostly 'right sized' to the range of national aeronautic engineering needs."

Nevertheless, portfolio planning can be more fully internalized and regularized and external stakeholders more regularly engaged in the process. The RAND study concluded that closer coordination and planning across DOD's Engineering Development Center and NASA could further identify national infrastructure overlap and reduce expenses on redundant facilities. The reviewers were troubled that "NASA's recent unilateral decision to close two facilities at Ames without high-level DOD review shows that progress has been spotty."

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[10]NASA, *The NASA Aeronautics Blueprint: Toward A Bold New Era of Aviation.* NP-2002-04-283-HQ. (Washington, DC, 2002).
[11]Philip S. Anton et al., *Wind Tunnel and Propulsion Test Facilities: An Assessment of NASA's Capabilities to Serve the National Needs*. MG-178 RAND (Santa Monica, CA: National Defense Research Institute, 2004), pp. xviii-xxi.

Another positive sign is increasing recognition among ARMD managers of the need for balance between short and long term, although disagreement remains about what mix is appropriate. One manager we interviewed tries in an ad hoc way to spend 20 percent of his research money on "high promise breakthrough kinds of things" that "you're not sure are going to work," an investment he described as "minuscule." But he admitted that most of those resources are contained in related project budgets. However, because all budgets are projectized, this less than transparent approach to portfolio balancing defeats the best-practice possibilities for strategic-level conversations and healthy debate. The next steps should be to make the need for a balanced portfolio uniformly understood organization-wide and to bring the planning and debate more into the open. The strategy of balance should be explicit as it is at DARPA, for example, which aims for breakthroughs and focuses on high-change-potential projects, yet also explicitly maintains a portfolio across relatively near, medium, and longer term R&D.

The committee also supports an initiative in ARMD's FY 2006 budget to create a central pool of funds for exploratory research. The associate administrator indicated to Congress that "a level of funding will be reserved for 'seed corn' research."[12] This would bring longer term exploratory thinking out from hiding and into the open as an explicit management tool.

MANAGEMENT FOR TECHNOLOGY TRANSITION

In the final analysis, the value to the nation of ARMD R&D comes through implementation. NASA aeronautics strategy documents regularly acknowledge this: "We measure success by the extent to which our results are used by others . . . ."[13] NASA has achieved some notable successes in this regard. One example is the agency's structural analysis software, NASTRAN, which began development in the mid-1960s and continues to serve as the basis for a large fraction of the finite element analysis software used ubiquitously today in industry in almost every area of mechanical structure and design.[14] According to congressional testimony by a former General Electric official, the Energy Efficient Engine Program and the Quiet Engine Program of the 1970s and 1980s identified technologies that eventually found themselves in product lines such as the GE90 family of engines that powers the Boeing 777 today. They have also spawned products like the Genx, which will power the Boeing 787 tomorrow. Without this research, GE would not have the composite fan blades, high pressure-ratio core, or low emission double annular combustor that put the company in a leading position in the industry.[15]

We believe that this record of successful transition to implementation is at risk today in ARMD.

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[12]Dr. J. Victor Lebacqz, associate administrator for aeronautics research, National Aeronautics and Space Administration, "Appropriations Subcommittee Staff Briefing," March 8, 2005.
[13]For example, see National Aeronautics and Space Administration, *Aerospace Technology Enterprise Strategy.* NP-2003-01-298-HQ. (Washington DC, 2003), p. 5.
[14]John A. Alic et al., *Beyond Spinoff: Military and Commercial Technologies in a Changing World*. (Boston: Harvard Business School Press, 1992), p. 72.
[15]Statement of Dr. M.J. Benzakein, Chair, Aerospace Engineering, The Ohio State University, before the Subcommittee on Space and Aeronautics Committee on Science, U.S. House of Representatives, March 16, 2005. Available at http://www.house.gov/science/hearings/space05/Mar16/Benzakein.pdf.

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

This is particularly important for ARMD given its dependence on other entities to implement the technologies it develops. The implementation process is especially bifurcated in civil aeronautics, in which the FAA regulates and has to buy into new technologies operationally but lacks independent technical abilities to further develop them. Manufacturers must embody the technologies in equipment and products, but both private and public (e.g., FAA operations, local airport authorities, DOD) end users must signal their willingness to fund that embodiment though purchases. In contrast, on the space side of NASA and in the Department of Defense, the ultimate equipment purchaser also directs the fundamental R&D. Although not ensuring technology transition, such linked structures far more directly align decision-making incentives and communication. This poses a huge challenge for ARMD innovation.

The first and most obvious implication of this institutional separation from implementation is that, unless ARMD effectively partners externally, it will fail. The technology management literature is quite clear that engaging users is a particularly important element of successful innovation and implementation.[16] The users who would expect to be the recipients of ARMD innovations, in the main, require system-level innovation, for example, aircraft, engines, air traffic management systems. Advances in these broader areas require the integration of many technological advances. To be an innovative organization, where high-value solutions serve real needs and real requirements,

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.

A number of well-established techniques exist for engaging stakeholders in collaboration throughout the early and later phases. Such early customer engagement is, for example, central to quality function deployment (QFD), total quality management (TQM) and the house of quality. An extensive literature exists on these techniques.[17]

Although there is no substitute for developing an overall culture of essentially constant informal interaction with external stakeholders, more formal venues may also be valuable. These include joint planning committees with implementers; periodic customer review sessions in which the external stakeholders are asked to evaluate the relevance of ongoing work performed;[18] focus groups; and early phase incubation forums. Incubation forums involve

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[16]For example, Eric von Hippel, *The Sources of Innovation* (New York: Oxford, 1988), overviews a wide range of research evidence on the importance of lead users and mechanisms for identifying them.

[17]A quite readable product development–oriented primer on the multiple processes in customer needs assessment, TQM, QFD, and house of quality–related techniques is Karl T. Ulrich and Steven D. Eppinger, *Product Design and Development, 2nd Edition*. (Boston: Irwin McGraw-Hill, 2000). See also the QFD Institute, available at www.qfdi.org.

[18]If these sessions yield glowing remarks from the reviewers, they probably do not involve real customers. In the committee members' experience in industry, real customers with real needs do not usually view innovations altogether positively. When they do compliment the solutions, they

external stakeholders in developing clear definitions of needs and seeking answers to questions such as “What five solutions don't exist, but if we had them, would help break through this problem?” Participants in these sessions tend to be not only experts in the implementation area but also professionals outside that field.

ARMD faces a number of significant barriers to effective long-term engagement of external partners. The foremost is the extraordinary variance across ARMD’s sub-missions in terms of the relevant partners and partner skill sets. Key partners include, but not exclusively, NASA space operations, the multiple branches of DOD, the Department of Homeland Security (DHS), the Department of Transportation (DOT), the Transportation Security Administration (TSA), the National Transportation Safety Board (NTSB), FAA air traffic management operations, FAA acquisition and R&D functions, FAA regulatory functions, FAA’s foreign counterparts, air traffic controllers, local airport authorities, industry and university wind tunnel research users, large airframe manufacturers, small aircraft manufacturers, avionics manufacturers, information technology systems providers, propulsion system manufacturers, and university aeronautics and related departments. Working closely with that numerous and diverse a group of stakeholders by bringing them in early and jointly prioritizing projects represents a daunting challenge.

A second impediment relates to organizational structure. ARMD is embedded in a space organization that itself routinely implements new technologies. Top-level NASA administrators come predominantly from the space side. Transitioning new aeronautics technologies may not be understood as a different and in some ways more challenging task than it is with space technologies. The failure to engage stakeholders fully in the restructuring of VSP is not a good sign that NASA fully understands the importance of consultation. Its after-the-fact approach runs counter to best practice.

ARMD administrators frequently take credit for substantive coordination with external stakeholders and may believe they are doing an adequate job of it. For example, in a congressional staff briefing, ARMD highlighted the following activities:

- ARMD associate administrator visits to industry and government customers to understand their business plan and technology needs, discuss ARMD plans, and identify gaps in ARMD research;
- Reestablishment of the Industry Technology Leadership Team to obtain a broad perspective on aeronautics research from corporate chief technology and chief operating officers;
- Populating the Aeronautics Research Advisory Committee with people of stature from industry; and
- Participation in the Joint Aeronautical Commanders’ Group (DOD Joint Logistics Commanders).

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tend to set higher expectations for the future. Receiving high marks from review panels is indicative of having perfunctory reviews or inattentive reviewers. Providers can be easily misled.

Yet we observe a tendency to outsource strategizing and customer surveying, resulting in a long series of reports and customer surveys performed by external consulting organizations.[19] To a degree this is appropriate, for example when it is likely to elicit more candid commentary; but it may also reflect lack of skill in NASA, or preoccupation with day to day operations, or both. Another sign that the institutional culture is not sufficiently attuned to understanding stakeholder needs and capabilities was a decision a few years ago to cut funding for ARMD scientists to participate in national scientific meetings. This not only reduced the visibility of NASA's national aeronautics research role in national leadership but also opportunities for midlevel ARMD staff to interact informally with external stakeholders in professional forums. Integrating stakeholder needs analysis into technology management processes appears not to be regarded as an essential core competence.

When engagement does take place, the results are sometimes ignored. The extensive conversations and joint planning with industry during 2004 for the Vehicle Systems Program were a positive development and recognized as such by both ARMD and industry participants. But these consultations did not serve as the basis for the FY 2006 budget proposals, narrowing the VSP agenda to four "breakthrough" programs. First engaging and then ignoring key stakeholders risks the portfolio's becoming irrelevant.

ARMD's efforts to avoid the appearance of promoting "corporate welfare" may themselves be an obstacle to sustained involvement of industrial partners. The supersonic aircraft programs of the 1980s linked the NASA aerospace centers together closely with industry. But when those programs were cut in late 1990s and the funds disappeared from the budget rather than being reallocated to other activities, the lesson for many NASA employees was that the aeronautics program had gone too far in engaging and helping commercial interests. One former NASA manager told us it "significantly and adversely colored subsequent relations with industry." ARMD managers endeavor to avoid criticism and its potential adverse budget consequences, but this makes the hand-off to implementers more difficult.

Relations with commercial partners are not, of course, the only relationships crucial to innovation. With the possible exception of the activities of the Joint Planning and Development Office (JPDO), discussed below, ARMD interactions with the Federal Aviation Administration have been hindered by structural impediments. Planning and coordination of research activities has been the responsibility of the acquisition and research part of the FAA, whereas the introduction and use of new technology depends on FAA operations. The operational divisions of the FAA are preoccupied with the immediate problems of managing the air traffic control system and therefore may not have been involved in the planning of the research. The perception in ARMD is that FAA operations tends to view the introduction of the technology into an already overburdened system as infeasible or high risk, requiring major efforts in training controllers and changing accustomed behavior. At worst, this has led to the abandonment of some NASA projects. At best, it makes field-testing new concepts difficult.

A related hurdle is uneasy relations with the air traffic controllers union, the Professional Air Traffic Controllers' Association (PATCO), whose code of responsibility affirms that decisions must be made and communicated by controllers. It is ARMD's perception that technologies that would reduce controllers' discretion or bypass their communication with pilots face strong resistance. Yet ARMD has worked on systems that would develop instructions to

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[19] See the large number of reports on strategy and customer assessment done for NASA aeronautics by Science Applications International Corporation, Technology Services Company, Arlington, Virginia. Available at http www.aerospace.nasa.gov/library/da/study/index.htm.

pilots and communicate them from the ground directly, not through controllers. With these and all other stakeholders, ARMD needs to actively manage such barriers. The best-practice approach is to work directly and regularly with the stakeholders to thoroughly understand their needs and concerns, working with them to anticipate such issues early in the technology development process rather than encountering roadblocks late in the development cycle.

A final impediment to engaging external stakeholders is a perception that NASA has not always carried through on its commitments. The chopping and changing associated with the 2005 VSP reconfiguration is a case in point. A large literature suggests that developing trust and fairness are key ingredients to best-practice innovation partnerships.[20]

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

This poor reputation stems from several sources. One, which we address in more detail below, is the recent implementation of full-cost pricing for the use of facilities. This has very strongly discouraged some potential partners. A remarkably uniform view among our interviewees and workshop participants was that full-cost accounting, as one participant put it, works against "the opportunity for relationships" because in the absence of NASA funding for facilities "the customer has to put up unreasonable cash if it wants to use it." The charges are perceived by partners as not only uncompetitive but also unfair. A second source of the lack of confidence is the periodic reshuffling of priorities in the annual budget process. With aeronautics taking a back seat relative to space priorities, ARMD programs can and regularly have been arrested midstream with the approval of OMB. This perception of ARMD as an unreliable partner over time is a significant impediment to collaborative planning and ongoing engagement. Partners feel they cannot count on ARMD to continue long-term projects and so hesitate to enter into them.

There are nevertheless some encouraging signs for early and sustained involvement of external partners in ARMD activities, even though its organizational culture as a whole falls short of best practice. We are cautiously optimistic about the potential of the Joint Planning and Development Office to coordinate planning for the future of the nation's air traffic management (ATM) system. Established by Congress under the FAA and including representatives of the Departments of Homeland Security, Transportation, Defense, and Commerce as well as NASA, the FAA, and the White House Office of Science and Technology Policy, JPDO involves a series of collaborative teams engaged in roadmapping and prioritizing technologies for various aspects of the nation's future airspace management system. JPDO delivered its first major product, the "Next Generation Air Transportation System: Integrated Plan," to Congress in December 2004. It lays out a multiagency agenda and governance model intended to facilitate cross-agency

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[20]See, for example, T.K. Das and B-S Teng, "Between Trust and Control: Developing Confidence in Partner Cooperation in Alliances," *Academy of Management Review* 23(3, 1998), pp. 491-512; Y.L. Doz and G. Hamel, *Alliance Advantage: The Art of Creating Value Through Partnering*. (Boston, Harvard Business School Press, 1998); C. Lane and R. Bachman, eds., *Trust Within and Between Organizations: Conceptual Issues and Empirical Applications*. (Oxford, Eng.: Oxford University Press); N. Lazarec and E. Lorenz, eds., *Trust and Economic Learning*. (Cheltenham, Eng.: Edward Elgar Publishing, 1998); L.G. Zucker, "Production of Trust: Institutional Sources of Economic Structure, 1840-1920," *Research in Organizational Behavior* 8 (1986), pp. 53-111.

cooperation. This joint planning document in turn has guided NASA in developing its FY 2006 budget proposal.[21]

Although we have not evaluated this report nor closely examined the functioning of the JPDO, in principle this is the kind of external collaboration, yielding joint recommendations taken seriously in ARMD portfolio planning, that can serve as a model for other areas of ARMD activity.

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.

JPDO is nevertheless limited in its capacity to raise the profile of the need for modernization of air traffic management and the role of technology development. It has, for example, no independent budget authority, although it can influence participating agency budget allocations. One option suggested to our committee is to shift control of the airspace management portion of the ARMD budget, together with the FAA's Air Traffic Organization R&D budget to JPDO. JPDO could contract with ARMD to provide technical competency through secondment of personnel. The result could be an organization with more influence to protect and increase resources for development of an advanced air traffic management system with much greater capacity. But this is dependent on an evaluation of the JPDO's performance to date, justifying the promise of the concept.

Another example of ARMD's engagement of external partners is the Access 5 Alliance, a jointly supported NASA and industry collaborative effort on technical, regulatory, and procedural issues related to high-altitude, long-endurance remotely piloted aircraft.[22] Begun in 2004, the alliance plans to take technology to demonstration. Planning and prioritization are collaborative. NASA participates using a nontraditional funding approach whose flexibility we think is worth exploiting more often, a joint sponsored research agreement. Similarly, NASA also quietly participated in the Super 10 Initiative developing supersonic business jet technologies with all the large airframe and engine firms, by most reports working effectively and collaboratively.[23] Finally, we encourage experiments like the science and technology park at the Ames Research Center in engaging corporate and educational partners.[24]

Despite the nod of ARMD strategy documents to measuring success by implementation, project managers told us that transition planning is not a regular expectation either as projects come up for consideration or when they commence. Some managers do include plans for how their project's outcome might transition to users, but such explicit planning appears limited and ad hoc. This runs counter to technology management best practice.

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[21]See the emphasis on JPDO recommendations in recent congressional testimony of Dr. J. Victor Lebacqz, associate administrator for aeronautics research, National Aeronautics and Space Administration, "Appropriations Subcommittee Staff Briefing," March 8, 2005.
[22]Available at http://www.access5.aero/access5_custom/what.html.
[23]M.V. Lowe, "Meet the Supersonic Business Jet," *Popular Mechanics*, Nov. 16, 2004.
[24]National Research Council, Board on Science, Technology, and Economic Policy. *A Review of the New Initiatives at the NASA Ames Research Center*. (Washington DC: National Academy Press, 2001).

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 prioritization process.

Transition planning starts with a clear understanding of who the receiving customer is, their needs and abilities to implement, their early involvement jointly identifying steps, deliverables, milestones, and performance metrics for tracking progress and changing course when needed, and their agreement to work to internalize and implement the results if successful.

Transition planning works at DARPA, for example, through two methods: taking technologies to the point of working demonstration and validation prototypes (a DARPA prototype showed the effectiveness of stealth technologies, for example) and working with industry to identify transition opportunities.[25] DARPA has an easier task, however, in that its stakeholders have substantial independent ability to implement technologies. DARPA is not responsible for delivering final prototypes nor for maintaining infrastructure, relying instead on external performers, including ARMD wind tunnel facilities.

Effective transitioning can unfortunately raise costs. Transition planning experience at the Air Force Research Laboratory (AFRL), for example, suggests that management needs to be prepared to invest more per project. This in turn means narrowing activities and what an AFRL manager described to the committee as a fundamentally different approach to R&D, focusing on customer needs and capabilities and arriving at integrated solutions, not simply discrete technologies.[26]

Notwithstanding the cost implications of carrying development further in some cases than has been the practice, ARMD needs to exercise more flexibility in applying the concept of technology readiness levels (TRLs). Best practice suggests that

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.

The AFRL experience, described in the committee's second workshop, is instructive. According to Colonel Mike Leahy, taking a broad array of different technologies "to TRL 4 made no sense anymore. Some had to go to flight [i.e., TRL-6, flight test in a relevant environment], some did not. It took tough calls."[27] Recognizing the significant potential budget consequences, ARMD needs to consider taking technologies further than it has been accustomed to doing or believed it had the latitude to do. Apart from the nature of the technology, much depends on the sophistication and resources of the customer. In the case of the FAA, for example, its operational mission and lack of strong technical skills may dictate that ARMD

[25]As one example of the DARPA requirements for transition planning and taking technology to demonstration, see "Proposer Information Pamphlet (PIP), High-Precision Long-Range Laser Designator/Locator (HPLD)," Defense Advanced Research Projects Agency, Advanced Technology Office, BAA05-01. Available at http://www.darpa.mil/ipto/solicitations/open/02-21_PIP.htm.

[26]Testimony of Col Mike Leahy, Air Force Research Laboratory, to the committee, January 18, 2005.

[27]Testimony of Col Mike Leahy, Air Force Research Laboratory, to the committee, January 18, 2005.

needs to take whole systems to TRL-6 full flight demonstrations and through midterm R&D. In other cases, it is natural for ARMD to conduct high-risk breakthrough research while leaving more downstream technology development to its partners. Both DOD and the commercial airframe and engine manufacturers have huge budgets, extended implementation expertise, and their own R&D infrastructure. For these partners there is less need for ARMD to take technologies as far. One workshop panelist put it succinctly, "NASA can't toss the ball to FAA at a low TRL level. There is no one to catch it. But they can in propulsion. GE can catch." So too, with the airlines in air safety. Although the airlines' financial condition limits their investment in the short term, they have large private incentives to improve safety, making it unlikely that ARMD need go all the way to a high level in air safety systems requiring their implementation.

ARMD has demonstrated an ability at the individual project level to field-test air traffic management demonstration modules working with the FAA. Research transition plans (RTPs) have worked in FAA's Free Flight Phase II office.[28] RTPs outline the roles and responsibilities of NASA and the FAA in transferring results.

Another successful example was the traffic management adviser (TMA), providing controllers advice about managing traffic flow into airports most efficiently. One ARMD manager described the process to us: "The need for demonstrating TMA was created by the Atlanta Olympics. TMA was carefully implemented on a shadow basis alongside the existing system, with displays configured to suit controllers. But it was developed within the constraints of the current system. It only deals with the planes crossing into the airport airspace. This works fine for DFW (Dallas-Fort Worth Airport), where the airspace is 200 miles in all directions. But things are much more complicated in the Northeast. So we've developed something called TMA multicenter. There are no technological obstacles, but it depends on sharing among air traffic controllers in different locations . . . . We had to become more responsive to the FAA, not because they wanted it, but to be more effective we had to stop pushing on a rope." Although the manager was expressing some frustration, we take it as a positive sign that ARMD recognized the need to understand customer needs and limitations. The result was not only successful implementation but also increased trust and cooperation, leading to development and adoption of other decision support tools. "As a result of TMA success, the FAA decided we weren't solely eggheads. We've jointly developed a ground management system that is being implemented at Memphis and Louisville. It is very popular with the cargo carriers, FedEx, and UPS." Transitioning techniques of this sort need to be used systematically, not depend on individual managers' being attuned to the circumstances of their customers.

Often there need to be changes on the customer side to facilitate successful transition management. An example is the decentralization of the FAA's acquisition functions. ARMD is now compelled to deal with each of the operating and regulatory units rather than exclusively with the Office of Research and Acquisitions, which was removed from operations. Although some AMRD personnel thought this change complicated NASA's interaction with FAA, in fact it may lead to more transparency and a more robust understanding of the customer more widely diffused throughout the ARMD organization.

The committee is also encouraged by ARMD's new approach to management of the Aviation Safety and Security Program. It includes plans to "transfer these advanced concepts, technologies and procedures through a partnership with the Federal Aviation Administration (FAA) and the Transportation Security Administration (TSA) in cooperation with the U.S.

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[28] *Review of NASA's Aerospace Technology Enterprise*, pp. 46-47.

aeronautics industry."[29] In this context, NASA has signed memoranda of agreement and memoranda of understanding with other agencies. Although touted as a success, as the FY 2006 budget plan suggests it remains to be seen how well it is implemented in practice and becomes an institutional norm.

FLEXIBLE HUMAN RESOURCE PRACTICES AND INCENTIVES FOR CREATIVITY

Accelerating innovation in large part means managing change, particularly in dynamic technological fields such as the information technologies central to ATM modernization and to aeronautics design and simulation today. Managing change requires incentives for new ideas, flexibility, ongoing adjustments in portfolio priorities, midcourse corrections in projects, and regular realignment of staff and skill sets. ARMD innovation suffers significantly because of limited incentives for exploring creative new ideas, as well as constraints on its staffing flexibility, some of them legislative, and some structural and organizational.

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.

One significant change in personnel policy outlined in the FY 2006 ARMD budget proposal is an overall reduction in the workforce, albeit a more rapid reduction of civil service positions than of contractor positions.[30] In this section we consider other human resource practices that could enable more flexibility and innovativeness within existing structures.

The new ideas and fresh thinking that are often necessary ingredients in innovation are injected in part by bringing in new people. Finding ways to introduce the new people in an environment of significant budget decline and civil service regulations is particularly challenging. Nevertheless, we believe increased flexibility is possible by expanding several techniques already in partial use at ARMD and experimenting with additional human resources ideas used elsewhere.

Personnel rotation is one approach that is common in industry.[31] Similarly, DARPA explicitly rotates all technical program managers, who come to the agency on four-year commitments, seconded from then returning to their home organizations. DARPA believes this

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[29]Dr. J. Victor Lebacqz, associate administrator for aeronautics research, National Aeronautics and Space Administration, "Appropriations Subcommittee Staff Briefing," March 8, 2005.
[30]Dr. J. Victor Lebacqz, associate administrator for aeronautics research, National Aeronautics and Space Administration, "Appropriations Subcommittee Staff Briefing," March 8, 2005. Also see NASA's FY05 Initial Operating Plan, particularly the description (p. 6) of actions and intentions regarding buyouts of civil servants during FY 2005 and FY 2006, including "voluntary separation incentives" for employees in "excess competency areas." Available at http://www.nasa.gov/pdf/107781main_FY_05_op_plan.pdf.
[31]The innovative oil services firm Schlumberger, for example, has an aggressive strategy, intentionally maintaining both high turnover and high international mobility within the firm to foster innovation and diversity at all their locations worldwide. See Busher et al., 2003.

rotation revitalizes innovation and helps promote technology transfer at the same time.[32] In fact, DARPA has no permanent program manager positions. This also allows flexibility for bringing in the most relevant expertise as priorities and competency needs evolve. An added benefit would be increased communication and joint understanding of external needs and capabilities. Several ARMD managers we interviewed noted that the lack of personnel exchanges among NASA, the FAA, and the airlines inhibited effective cooperation in ATM modernization. "Our customers don't know who we are," one said, adding that unless ARMD "can understand the end user's requirements, we are shooting in the dark."

<u>Recommendation 5-B</u>: 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 transitioning.

In the near term, this could entail expanded use of formal Intergovernmental Personnel Act (IPA) exchanges.

Short of full secondment,

<u>Recommendation 5-C</u>: NASA should foster external customer contact early in and throughout the careers of ARMD technical personnel.

This not only establishes from the start expectations and norms of customer engagement but also serves as a tool for personnel development and retention, making early job assignments more dynamic and interesting. Some high-technology firms that send their technical employees to interact with customers in the first few months of their careers report quite positive results for both development and retention of the most innovative employees.[33]

Innovative human resources practices can also encourage creativity on the part of existing personnel. We suggest several approaches. First, despite civil service promotion and pay structures,

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

The AFRL program is a contribution-based reward system that allows for the rapid advancement and pay increases for new people based on merit, not where or how long they serve.[34] AFRL implemented this scheme as part of the transition from four super laboratories to a single laboratory and in anticipation of significant reductions in research budgets following the end of the cold war. A similar window of opportunity may now exist for ARMD to implement new personnel management policies in the context of its own downsizing.

Expanding innovation flexibility can also mean the freedom for individuals, for minor fractions of their time, to pursue their own ideas. Philips Central R&D Laboratory, for example,

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[32] Defense Advanced Research Projects Agency, "Welcome to Employment Opportunities with DARPA," last updated October 1, 2003. Available at http://www.darpa.mil/hrd/.
[33] Busher et al., 2003.
[34] Testimony of Col Mike Leahy, Air Force Research Laboratory, to the committee, January 18, 2005.

quite effectively allowed a few percent of researchers' effort to be devoted to investigator-initiated work, outside any directed project.[35] For many years, the lab hosted an internal fair or poster day, in which employees showcased this work to each other. In recent years, management opened that day to external customers, and they report that the nonpecuniary social incentives and the level of stimulated conversation resulted in considerably increased quality, utility, and relevance of the self-directed work. Philips's experience suggests that the cost of such a program to ARMD could be minimal. NASA center directors do have available to them the Center Director Discretionary Fund, which allows them to fund basic research activities. This funding allocation (approximately $2 million per center) is under intense scrutiny by OMB examiners, who have concerns about the unstructured nature of this program. Its continuation year to year is problematic. However, for the present the three aeronautics centers do have a small degree of flexibility in the funding of new ideas. The committee supports this arrangement and encourages its expansion.

<u>Recommendation 5-E:</u> 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.

Another low-cost alternative to traditional requests for proposals (RFPs) for stimulating innovative ideas would be to invite ideas from nonemployees via significant competitions. Highly successful examples exist elsewhere. Nearly 200 independent teams entered the 2005 DARPA Grand Challenge for an autonomous ground vehicle for rugged terrain.[36] The $2 million prize is a remarkably limited expense considering the thousands of people nationwide it encouraged to tackle the problem. Similarly, the $10 million Ansari X-Prize led to the first non-government-sponsored human space flight.[37] By establishing a broad goal, without constraining or dictating either the solutions or who participates, such high-profile prizes generate large numbers of ideas from a wide array of viewpoints. The prizes are large enough to attract significant media and public attention but are quite limited investments by aerospace standards.

NASA recently launched the Centennial Challenges program of prize contests related to space exploration.[38] The largest prize announced thus far—the 2006 Space Elevator Climber Competition—is only $150,000. Although this is an encouraging start, the program does not target aeronautics challenges, and the prize levels may not be large enough to generate both serious effort and public attention.

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

The committee recognizes that flexible personnel management practices can be disruptive for organizations and employees. Staffing is often tied to particular programs and projects.

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[35] Busher et al., 2003.
[36] DARPA News Release, February 15, 2005. Available at http://www.darpa.mil/grandchallenge/GC05FinalApps2-15-05PR.pdf.
[37] See http://www.xprizefoundation.com.
[38] See http://exploration.nasa.gov/centennialchallenge/cc_index.html.

Increasing employee mobility through rotations and secondments may impose financial penalties in transportation and temporary housing and may not be attractive to employees with families.

In general, workforce development and recruiting has not been a priority in ARMD's downsizing environment. There has been little turnover, and the workforce is aging. Some employee educational programs exist NASA-wide, but with limited new hiring, aeronautics is not working closely with many higher education institutions. Moreover, education programs at NASA tend to focus on K-12 outreach, aiming to excite young people about space science. This approach does not compare favorably with the institutional support and aggressive recruiting by universities, often through partner-schools programs, and large high-technology corporations.

There are scattered examples of innovative human resource practices in NASA's aeronautics program. The Ames Research Center recently established a university affiliated research center (UARC) and a joint university-level engineering program with leading west coast universities. The UARC, a collaboration with the University of California, provides for faculty to be located adjacent to Ames to work on problems of common interest. In the joint university engineering program, Ames provides seed money that supports graduate students to investigate new concepts in air traffic management and opportunities for students and faculty to interact with aerospace industry technical experts and government officials.[39] Stanford and two University of California campuses, Berkeley and Los Angeles, are participants in a program modeled after a similar East Coast program that includes the Massachusetts Institute of Technology, Princeton University, and Ohio State University. Again, the expenditure level, $120,000 per school per year, may be too small to have an important impact. By contrast, the General Motors PACE (Partners for the Advancement of Collaborative Engineering Education) program distributes several million dollars each to more than 30 universities worldwide.[40]

The Langley Research Center instituted another practice being used at one other center that could be duplicated elsewhere. The center reserves $3 to 5 million per year of its general administrative overhead budget for "creativity and innovation." Researchers may submit a proposal to spend a part of their time on projects of their own conception. This is a more formal arrangement than we envision, but it nevertheless conveys a strong signal that individual imagination and initiative are valued. Believing that time rather than money is the more severe constraint on creativity, we encourage ARMD to institute more such programs for in-house investigators.

FINANCIAL MANAGEMENT TO MINIMIZE THE DISRUPTIVE EFFECTS OF EXTERNAL DEMANDS

Our last set of recommendations for fostering aeronautics innovation through NASA deals with the structuring of financial management at ARMD. To a significant degree, best-practice approaches to financial management aim to send clear signals internally and externally about the value of resources to help managers make efficient choices about how to allocate those resources within and across programs. When signals are not aligned with priorities, resource misallocation and inefficiency result. This is especially important to correct in an era of significantly declining resources.

[39]See *Aviation Week and Space Technology*, February 9, 2004.
[40]See http://www.pacepartners.org.

In FY 2004 NASA completed implementation of an agency-wide full-cost accounting system, which had been in planning and pilot-testing since 1995.[41] The purpose of full-cost accounting is to give mangers more complete information about the real costs of their activities, including the costs of personnel and facilities. Historically, program managers were not responsible for certain significant costs associated with their activities, including the actual cost of civil service personnel. As a result, agency administrators believed that the cost implications of program decisions were not well understood and appreciated. Although we strongly support the objective of achieving greater financial transparency, we think that attempting to achieve full-cost recovery pricing for both civil service and facilities use in NASA has had unintended negative consequences for aeronautics R&D activities.

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

Many ARMD research facilities have two characteristics that make full-cost recovery problematic. First, the facilities have significant long-term value from the standpoint of national security and economic competitiveness; this value should be reflected in public support rather than private user charges. Second, significant fractions of the total costs are essentially independent of short-term facility usage levels. For example, in our interviews at Langley we were told by administrators that the annual cost of operating Langley's transonic wind tunnel, in which virtually every U.S. aircraft has been tested, is mostly a fixed cost independent of how many tests are run in it; this may also be true of NASA's other operational wind tunnels.

Under NASA's full-cost accounting principles, however, prices are based on short-term (i.e., annual) facility usage levels and thus are sensitive to how many tests are run, even in places where operating costs may not vary in that manner. As a result, prices do not reflect the real impact of individual managerial decisions on costs, skewing the incentive signals. We see in this practice significant risk to the long-term financial viability of critical national aeronautics research infrastructure.

Full-cost pricing for ARMD facilities entails charging users the direct operating costs of their activities (e.g., materials, test components, support personnel, power) plus some prorated fraction indirect expenses (e.g., general maintenance, facilities upgrades, technician training, general administrative overhead). The latter is based on the fraction represented by the user in the total hours that the facility is used that year. When facilities run near capacity and have many users, each user appropriately absorbs a small fraction of the fixed overhead, maintenance, and equipment upgrade expenses. However, for a facility that in a particular year is used only occasionally, users who might account for only small fractions of total available capacity but large fractions of actual use in that year must absorb essentially all the costs for unused capacity. This can lead to less utilization as fixed costs are spread over fewer and fewer users, as has been the case with NASA's wind tunnels—in short, a "death spiral." Reportedly, fees increased on average 30-35 percent from 2003 to 2005, and, in one particular case, "utilization hours for the 20-Foot Vertical Spin Tunnel dropped 71 percent between 2003 and 2004, from 855 hours to 248 hours."[42]

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[41]See the *2004 NASA Cost Estimation Handbook*, available at http://ceh.nasa.gov/webhelpfiles/Cost_Estimating_Handbook_NASA_2004.htm
[42]Dave Schleck, "NASA Windtunnel Feed Under Review," *Hampton Roads Daily Press*, June 12, 2005.

At our workshops some aerospace industry representatives corroborated their increasing reluctance to use NASA facilities. Gulfstream qualified all four of its most recent aircraft in either France or the United Kingdom, not in the United States,[43] despite the fact that the federal government is the company's largest customer. Similarly, Boeing is going to Toulouse for Dreamliner 787 testing. Both firms report that NASA facilities are not competitive under full-cost charging. The result is that U.S. firms are supporting European infrastructure while reducing facility usage rates in the United States. This raises charges to other users, contributing to a further drop in utilization.

This pricing policy applies equally to internal NASA users, leading to somewhat arbitrary cross-program subsidization. In ARMD this is particularly burdensome for air traffic management research, which tends not to be fixed capital intensive but rather relies on people and on rapidly advancing information technologies. In some of our interviews, project managers suggested that ATM projects end up paying high overhead to support facilities used mainly for non-ATM research. To make matters worse, Congress prohibits NASA from charging administrative overhead expenses on directly funded earmarked projects,[44] a growing fraction of ARMD discretionary budgets, shrinking the base on which overhead expenses might be spread. This, in turn, has the effect of encouraging project managers to use contractor facilities and staff rather than civil service personnel whenever possible.

A former NASA official pointed to DOD's experience with full-cost recovery. He referred to a 1969-1972 failed experiment by the Air Force Arnold Engineering and Development Center. For that period DOD charged users full average costs, including all overhead and equipment capacity, while DOD funded none itself. This led to an unsustainable steep decline in revenue,[45] leading DOD to reverse the policy. Since then, DOD has funded more than 50 percent of AEDC's total annual costs, sharing the burden with users in order to retain an important national strategic asset and insulate it from short-term variations in usage.

Not only does full-cost pricing endanger particular facilities, but it also risks undermining relationships with external partners and internal research competencies. Our interviews with ARMD program managers suggest that some cooperative programs have been "one of the victims" of full-cost pricing, with repercussions for the competence of NASA employees. Because a customer has to put up all the funding to use a facility, substantive research collaboration with external partners potentially suffers: "government people become data generators and technicians for operating facilities to a greater extent and experts in the field to a lesser extent." This could result in the hollowing out of internal leading edge research competencies, with ARMD centers becoming simply a for-hire infrastructure with a high fixed cost.

Other external reviewers have expressed similar reservations about NASA's approach. The 2004 RAND study on NASA's wind tunnel and propulsion test facilities concluded that the full-cost pricing approach was "creating real risks to the United States' competitive aeronautics advantage"[46] by undermining the financial health of those facilities already underutilized—about one-third of the facilities in all. RAND found that "with declining usage and full cost recovery

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[43]Testimony of Dick Johnson, Gulfstream, to the committee January 18, 2005.
[44]See NASA's FY05 Initial Operating Plan, p. 3. Available at http://www.nasa.gov/pdf/107781main_FY_05_op_plan.pdf
[45]For more details see Philip S. Anton et al., 2004, p. 61.
[46]Anton et al., 2004, p. xiii.

accounting, these facilities run the risk of financial collapse."[47] As examples, the report cited two Ames facilities that "are unique and needed in the United States [but] have already been mothballed and slated for closure as a result."[48] The National Academies' *Review of NASA's Aerospace Technology Enterprise* also expressed concern about "unintended consequences" of full cost pricing—disincentives to use facilities to demonstrate new technologies, underutilization, and eventual closing of critical infrastructure.

The first task of NASA administrators, the administration, and Congress is to decide which aeronautics research facilities have unique, long-term national strategic and economic value. Once this is done, prices can be set to make optimal use of this capital investment. Marginal cost pricing is likely to be appropriate up to the point that a test facility is fully utilized. Anything that covers marginal costs produces revenue to help defray fixed costs without discouraging use of the facility. Full-cost pricing prices to restrict use. This is not an appropriate policy when facilities are underutilized.

<u>Recommendation 6-B</u>: AMRD should work with OMB and Congress to establish separate centrally funded budget lines for national infrastructure and facilities maintenance.

The RAND study pointed to this solution: "[Wind tunnel and propulsion test] facility operations are not funded directly by specific line items in the NASA budget . . . . [W]hen a needed facility is closed because of a lack of funding, there is a disconnect between current funding and prudent engineering need, indicating that the commercial and federal budget processes may be out of step with the full cost associated with research and design of a particular vehicle class and indicating a lack of addressing long-term costs and benefits."[49]

Without changes in accounting practices, much of the nation's aeronautics research infrastructure is in jeopardy. Indeed, NASA's current budget projections anticipate closing many of these facilities. We think NASA has erred in equating full-cost accounting with full-cost pricing. The two concepts are conceptually and practically distinct. Cost accounting information may be used not only for fee setting but also for accountability and performance measurement, budgeting, and managerial control. Average cost–based pricing is not considered best practice in industry[50] and is particularly problematic in circumstances of large fixed costs and high public value. NASA should centrally bear the fixed overhead costs incurred to maintain strategically important facilities. Users can be expected to bear the additional costs associated with their incremental use of facilities, but not full costs. In a shared cost model, users should not pay for unused capacity.

It appears to us that NASA is too narrowly interpreting the legislative requirements regarding full-cost accounting.[51] Federal standards do allow flexibility in implementation. In the

[47] Anton et al., 2004, p. xx.
[48] Anton et al., 2004, p. xxii.
[49] Anton et al., 2004, p. xvi.
[50] See, for example, Edwin Mansfield et al., "Pricing Techniques," in *Managerial Economics, 5th ed.* (New York: Norton, 2002). On the shift away from cost-based prices, see Roger Tang, "Transfer Pricing in the 1990s," *Management Accounting* 73(8), pp. 22-26.
[51] The most important related federal standards are the Statement of Federal Financial Accounting Standards (SFFAS) No. 4, Managerial Cost Accounting Concepts and Standards for the Federal Government. Available at www.fasab.gov/pdffiles/sffas-4.pdf. SFFAS No. 6, Accounting for Property, Plant, and Equipment. Available at http://www.fasab.gov/pdffiles/sffas-6.pdf.

case of aeronautics R&D, there are broad benefits to the nation above and beyond the benefits to specific users, and sharing costs for such public purposes is even within NASA's own standards for full-cost recovery.[52] These require full-cost charges only when special benefits accrue to users, not when there is general public value. We encourage a more liberal interpretation of these full-cost recovery requirements.

There are some recent hopeful signs that ARMD administrators are aware of the potential problems of full-cost recovery. The ARMD associate administrator's briefing[53] on the FY 2006 budget defends the full-cost initiative but acknowledges the need for flexibility: "Full cost accounting is necessary to understand the return on taxpayer investment . . . [but] NASA is developing innovative ways to maintain flexibility in human resources and institutions. . . . One component of this new management approach may be a direct ARMD investment in key facilities to ensure longer-term facility sustainability." In another initiative, NASA's new administrator, Michael Griffin, has directed a group of headquarters officials to study how to "better manage NASA research facilities in a full-cost environment."[54] We hope that these deliberations embrace the principle of central funding of shared fixed costs and incremental pricing for internal and external users.

Another candidate for centralized budgeting is contingency funds, outside specific projects, enabling more flexible responses to unforeseen research contingencies. Rigid project silos with inflexible milestones that do not tolerate failure or changes of direction are a recipe for narrow, short-term research agendas.

<u>Recommendation 6-C</u>: 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.

ARMD project managers told the committee they have no official contingency budgets, centrally funded or otherwise. Some report that they occasionally manage to create ad hoc contingency accounts, but that this is dependent on individual managers and does not enable cross-program conversations about relative priorities. Explicit contingency funds to which project managers could apply would make these decisions more transparent and more likely to be in alignment with the overall mission. Another option is an agency-wide central pool to carry civil servants whose projects are cancelled. This would not yield short-term resource savings overall, but it would increase flexibility and better align managerial incentives at the project level.

Two principal challenges in dealing with the inevitable uncertainties in leading edge research are the rigidity of the annual appropriations process and the constraints imposed by overreliance on project budgets. The short-term planning needed to accommodate annual budget cycles and the associated fluctuations in priorities are especially challenging for long-term research. Neither project managers nor top NASA administrators can change major project milestones without OMB approval. The perception expressed to us by ARMD management at

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[52]NASA, Review, Approval, and Imposition of User Charges, Policy Directive NPD 9080.1F, October 14, 2004. Available at http://nodis3.gsfc.nasa.gov.
[53]Dr. J. Victor Lebacqz, associate administrator for aeronautics research, National Aeronautics and Space Administration, "Appropriations Subcommittee Staff Briefing," March 8, 2005.
[54]Schleck, 2005.

Langley, for example, was that anything they defined as a contingency would get cut by OMB. Moreover, civil service regulations severely restrict midstream staffing changes.

In the past, NASA aeronautics had a systems technology program and a base research and technology program. The former was composed of projects conceived, funded, and operated as projects, with funding terminated in some cases. The basic R&D work was longer term and continuously supported. One center official observed that today all activities are funded in five-year chunks with a beginning and an end, making it difficult to take a long-range point of view. "Now that there's no more R&T base, there's a bias in favor of [finite outcomes] and therefore against experiment and innovation."

One approach begun as a small pilot program is the Working Capital Fund (WCF). The legislative authority for this new formal structure enables more budget flexibility for capital and personnel, not tied to direct annual appropriations.[55] NASA is able to establish WCFs for internal business-like entities with customers for products and services. Funds received from customers can then be expended as needed, without regard to fiscal year limitation.[56] NASA began a pilot WCF in FY 2005 with an information technology procurement group, called Science and Engineering Workstation Procurement, that acquires computers and related equipment on a transfer fee basis for programs throughout NASA. Because the WCF legislation extends to services, consideration should be given to extending the idea to aeronautics wind tunnel facilities and to R&D services more broadly. Annual budget cycles would apply to the procurement projects, but management of the provision of services would have considerably more discretion and enable longer term planning.

<u>Recommendation 6-D</u>: ARMD should explore establishing Working Capital Fund structures for wind tunnels and aeronautics R&D services.

Earlier we described the increasing incidence of congressionally directed projects, most of which are unfunded, that is, they are mandated with the expectation that NASA will perform the tasks within the agency's current budget. The managers we spoke to complained not about their value—"most are good things to do" —but about their disruptive effective on planning. We suggest that every effort be made to align these activities with established programs. This may be most feasible with projects that reflect congressional concern that some important public good objective is being neglected in NASA's planned activities. However, some earmarked projects bear little relationship to NASA's mission. In those cases, a separate budget account should be created for managing them.

<u>Recommendation 6-E</u>: 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.

The immediate effect of a separate budget for congressionally directed projects would be to reduce the apparent size of the balance of the ARMD budget and seemingly narrow the

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[55] See NASA, Working Capital Fund, available at http://www.nasa.gov/lb/offices/ocfo/references/ocfo_WCF_detail.html

[56] See http://www.nasa.gov/pdf/107225main_FY03%20approps%20working%20cap%20langOriginalFINAL.pdf.

discretion of associated program managers. However, real discretion over the balance of the program would increase. In 1995 approximately one-quarter of DARPA's $2.5 billion budget was earmarked.[57] The director ceded control and responsibility for the earmarked projects to the military services, reducing DARPA's budget to $1.9 billion. But the transfer significantly improved budget flexibility and stability, resulting in a healthier technical management environment. NASA should consider following this model.

ORGANIZATION OF NASA AERONAUTICS R&D

As noted in the preface to this report, the administration's policy preference is to shrink ARMD's resources and portfolio on the assumption that a prominent government role in aeronautics R&D is no longer justified. The majority view in the technical, industrial, and academic communities appears to be the opposite: national technology needs in aeronautics are broad, compelling, and inadequately served by ARMD's declining resources. If the first course prevails, ARMD's subordinate role in NASA is appropriate. Its job will be to conduct fewer projects more efficiently while managing the contraction of three research centers. Eventually, lacking unique robust technical capabilities, it will go out of business. However, in the event that stakeholders mobilize effectively in support of an expansionist program, other forms of organization may be worth considering.

The President's 2004 Commission on Implementation of United States Space Exploration Policy (the Aldridge Commission), which among other things recommended a restructuring of NASA's research centers, considered the option of removing the aeronautics R&D program from NASA altogether. The principal reason the commission gave for rejecting that alternative was ARMD's involvement in addressing planetary atmospheric transportation as an eventual component of space exploration. In other words, space program needs dictated the conclusion, not the direct needs of aeronautics, even though an independent organization might be able to contract with NASA to support the Mars mission.

Another way to elevate the importance of the aeronautics portfolio and provide some protection from the demands of the space program is an agency-within-an-agency arrangement. In this case, too, NASA's space program could contract with NASA's aeronautics program for planetary aircraft work, but it would be more difficult to divert aeronautics resources to space activities. The Defense Department and the military services could similarly directly contract for aeronautics R&D services. DARPA has operated along these lines since its creation in 1958, reporting directly to the secretary of defense and operating independently of the other military R&D establishments. In a fee-for-service manner, DARPA subcontracts for most support services and infrastructure. Intelsat is a related example, in which bonds issued against user-fee revenue streams help pay for long-term technology and infrastructure.

Another precedent, closer in time and related in function, is the Air Traffic Organization, established within the FAA in February 2004 with its own chief operating officer and 36,000 employees.[58] ATO organizationally combines responsibility for air traffic operations, equipment acquisition, and research, separate from FAA's regulatory role.

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[57]Comments by David Whelan, Boeing Skunk Works, at the committee's workshop, January 18, 2005.
[58]See the May 20, 2005 FAA organizational chart, available at http://www.faa.gov/aba/html_pm/mi/files_doc/HQ-ORG.DOC.

The committee is not recommending either reorganization. That would be premature as well as beyond our mandate and competence. Rather we are underscoring our belief that the implications of the current policy divide are far-reaching—for NASA, for innovation, and for the nation's aviation sector. Until the divide is bridged, our management advice, although we hope useful, is a secondary priority.

Appendix A

Public Workshop Agendas

Board on Science, Technology, and Economic Policy

A Workshop on
"Aeronautics, Innovation, and the Public Good"

June 28, 2004

The National Academies
21st and C Streets NW
Lecture Room
Washington, D.C.

9:00 Welcome and Introductions

9:20 **Panel 1. Innovation in a resource-constrained environment: Lessons from the private sector**
- *Graham R. Mitchell, University of Pennsylvania*
- *John Terninko, Responsible Management Inc.*

10:20 **Panel 2. Innovation in a resource-constrained environment: Lessons from the public sector**
- *Bill Valdez, U.S. Department of Energy*
- *Gerald Hane, Globalvation*
- *Sara Clark, U.S. Department of Veterans Affairs*
- *Alan R. Shaffer, U.S. Department of Defense*

12:15 Lunch (Committee Members and Speakers)

13:15 **Panel 3. Public-private divide for technology innovation**
- *Richard John, Volpe National Transportation Systems Center*
- *Mike Scherer, Haverford College*
- *James G. McEwen, Staas & Halsey LLP*
- *John Alic, Consultant*

15:05 Break

15:15 **Panel 4. Priority setting for future NASA aeronautics**
- *Wesley L. Harris, Massachusetts Institute of Technology*
- *Simeon H. Austin, Pratt & Whitney*
- *Mark Anderson, Boeing Phantom Works*

16:45 **Panel 5. Technology Innovation in the NASA Context**

- *Victor Lebacqz, Office of Aeronautics*
- *Jaiwon Shin, Office of Aeronautics*
- *Terrence Hertz, Office of Aeronautics*
- *Richard Christiansen, Glenn Research Center*
- *Bruce Holmes, Langley Research Center*

17:35 Closing remarks

17:45 Adjourn

Committee on Innovation Models for Aerospace Technologies
Board on Science, Technology and Economic Policy
The National Academies

Workshop on
NASA's Roles in Aeronautics Innovation

Tuesday, January 18, 2005
Keck Center Room 100
National Academy of Sciences
500 Fifth Street, N.W.
Washington, DC

8:30 AM	Welcome and Introduction *Alan Schriesheim, Chairman*
8:45 AM	*Hon. Robert S. Walker, Wexler & Walker Public Policy Assoc.* Commission on the Future of the Aerospace Industry
9:30 AM	**Panel I: NASA's role in fundamental science and engineering R&D for a broad range of national aeronautical technology needs, public and private** Moderator***:*** *Deborah Wince-Smith, Council on Competitiveness* *David North, Aviation Week, ret.* *John Douglass, Aerospace Industries Association*
10:30 AM	Break
10:45 AM	**Panel II: NASA's role in R&D for the development of future airframes and aircraft propulsion systems** Moderator*: Joe Morone, Bentley College* *Dorothy Robyn, The Brattle Group* *David Whelan, Boeing Phantom Works* *Col. Mike Leahy, Air Force Research Laboratory* *Dick Johnson, Gulfstream Corporation* *Charles Boccadoro, Northrop Grumman Corporation* *Frank Cappuccio, Lockheed Martin Corporation**
12:45 PM	Lunch
1:30 PM	**Panel III: NASA's role in R&D in support of the nation's future air transportation management system and aviation safety** Moderator***:*** *Duncan Moore, University of Rochester* *Dorothy Robyn, The Brattle Group* *George Donohue, George Mason University* *Charles Keegan, Joint Planning and Development Office* *Richard Marchi, Airport Council International*

	Monte Belger, Lockheed Martin Corporation
	Holly Woodruff Lyons, House Aviation Subcommittee
	Vernon Ellingstad, National Transportation Safety Board
	Matthew Blake, Seagull Technology
3:00	Break
3:15	**Panel III Discussion**
4:30	Summation
5:00	Adjourn

Appendix B

Biographies of Committee Members and Staff

ALAN SCHRIESHEIM (Chair) consults on research productivity issues for corporate and government clients, strategic planning of research programs, and corporate-academic research partnerships. He also consults on issues related to the energy and utility sector.

Dr. Schriesheim is director emeritus of the Argonne National Laboratory. He was previously the chief executive officer of Argonne National Laboratory, having served as the director of Argonne from 1983 to 1996. He joined Argonne after a long career with Exxon Corporation. Dr. Schriesheim was the first national laboratory director to be recruited from industry, and he successfully launched a series of initiatives to diversify Argonne's core competencies, broaden its research scope, and expand its relationships with other government, academic, and industrial organizations, both nationally and internationally. During his tenure, Argonne undertook programs spanning the full range of science from high-temperature superconductors to developing biological microchips and sequencing the human genome to establishing a virtual-reality advanced parallel-processing computer center. Dr. Schriesheim was the driving force behind the establishment of ARCH, a separate entity between the University of Chicago and Argonne National Laboratory designed to commercialize technology from both institutions. He is the author or coauthor of numerous publications and holds 22 U.S. patents.

Dr. Schriesheim is a fellow of the American Association for the Advancement of Science, a member of the National Academy of Engineering, and a past chairman of the National Conference on the Advancement of Research. He has been active in community, educational, and cultural affairs, placing emphasis on developing the scientists of tomorrow.
Dr. Schriesheim holds a bachelor's degree from Brooklyn Polytechnic University and a Ph.D. in chemistry from Pennsylvania State University.

MEYER (MIKE) BENZAKEIN received his mechanical engineering degree in 1960. He received an M.S.M.E. in 1963 and a Ph.D. in engineering mechanics in 1967. He joined General Electric in 1967, where he served in a number of positions in advanced technology, project and product engineering. He led the CFM56 Engineering Program from 1984 to 1993 and the GE90 Engineering Program from 1993 to February 1995. In February 1995, Dr. Benzakein became general manager for engine systems design and integration, and in this capacity he had the responsibility for engineering leadership and technical oversight of GE Evendale Commercial and Military Aircraft Engines. In January 1996, Dr. Benzakein took over the position of general manager, advanced engineering programs, and held that position until he retired in October 2004. As leader of technology development efforts, he was responsible for GEAE front-end initiatives in driving technology maturation, strengthening the linkage between preliminary design, engine systems, and production hardware design. In 2004 he joined the faculty of the Ohio State University, where he is Wright Brothers Institute professor, chair of the Aerospace Engineering Department, and codirector of the Ohio Center for Advanced Propulsion and Power.

Dr. Benzakein has served on several National Academies' committees, including the Aerospace Engineering Peer Committee, the Committee on Review of NASA's Next Generation Launch Technology Program, and the Transportation Research Board's Committee for Developing an Aviation Environmental Design Tool. Dr. Benzakein was elected to the National Academy of Engineering in 2001. In that year he also received the Gold Medal Award from the Royal Aeronautical Society. He was elected a fellow of the Royal Aeronautical Society in 2002.

WILLIAM E. COYNE began a more than 30-year career with 3M Corporation in 1968 as a research chemist. From 1996 to his retirement in 2000, he was the senior vice president of research and development at 3M. He had responsibility for 30 technology platforms of the company. During his tenure as senior architect of 3M's R&D, the company invested more than $1 billion a year in research and significantly raised its new product targets. Each year, 3M now expects to derive 40 percent of its sales revenues from products that are new within the past four years. In 1999, 3M set a record of greater than $1 billion in first-year new product sales. In 1995, 3M was presented with the U.S. Medal of Technology by President Clinton.

Dr. Coyne served as sponsor of the 3M Technical Forum, an organization of thousands of 3M researchers who meet periodically in close to 30 chapters to share research, technologies, and ideas. One of 3M's greatest strengths has been its ability to combine and recombine technologies to create new families of products.

In 2001-2002, Dr. Coyne served as a member of the National Academies' Committee on Future Environments for the National Institute of Standards and Technology. He holds a Ph.D. in organic chemistry from the University of Virginia, an M.S. in pharmaceutical chemistry from the University of Toronto, and a B.S. in pharmacy from the University of Toronto.

JEROME (JERRY) J. GASPAR was until his recent retirement senior vice president, engineering and technology, and a corporate officer of Rockwell Collins. He was responsible for its engineering and technology organization, including the Advanced Technology Center, the Displays Center, and the Engineering Services Center. He was appointed to the position in June 2001.

Previously, Mr. Gaspar served as vice president of engineering and technology, a position he was appointed to in 1999. Prior to that he was appointed to develop the Enterprise Center of Excellence for flat panel display technology products. He joined the company in 1967 and has held positions of increasing responsibility in engineering, operations, and marketing, including vice president of programs for air transport systems.

Mr. Gaspar has served as a member of the Industrial Advisory Board of Sandia National Laboratories in Albuquerque, New Mexico, and is a member of the Industrial Advisory Board of Iowa State University. He is also a member of the Product Development and Management Association and the Project Management Institute. He earned a B.S. in electrical engineering from South Dakota State University and an M.B.A. from the University of Iowa.

STANLEY KANDEBO has spent nearly 20 years as a reporter covering aerospace and defense issues. He was educated as an engineer at the United States Military Academy at West Point, the New Jersey Institute of Technology, and the University of Pennsylvania. Early in his career he worked in the aerospace industry as a design engineer on several weapons projects, including the Harpoon and Tomahawk cruise missile programs. At the time of his committee service he was group director for editorial content development and assistant managing editor at

Aviation Week & Space Technology. He also created and edits the magazine's annual *Aerospace Source Book*. Mr. Kandebo holds an M.S. in chemical and biochemical engineering from the University of Pennsylvania and a B.S. in chemical engineering from the New Jersey Institute of Technology.

GLENN MAZUR has been disseminating and instructing quality function deployment (QFD) and related product development and innovation methods since their first introduction into the United States in the mid-1980s. His work as been recognized by the founders of these methods, receiving the Akao Prize® in 1998 and being selected as one of only two non-Japanese QFD Red Belts® (highest level) in 2000. His current positions include president of Japan Business Consultants, Ltd.; executive director of the QFD Institute (volunteer) and International Council for QFD (volunteer); chairman of the North American Symposia on QFD (volunteer); and faculty of total quality management at the University of Michigan College of Engineering (ret.). His other affiliations include senior member of the American Society for Quality and the Japan Society for Quality Control.

In addition to QFD, he has taught TRIZ (theory of inventive problem solving), analytic hierarchy process (prioritization and decision optimization), Kansei engineering (sensory and emotional requirements), Hoshin planning (strategic policy formation and deployment), total quality management (TQM), design for six sigma, and voice of customer analysis. Mr. Mazur holds an M.B.A. from the University of Michigan.

HENRY (HARRY) MCDONALD is distinguished professor, chair of excellence in computational engineering, at the University of Tennessee at Chattanooga, where he is engaged in establishing a research and educational activity in the field of computational engineering.

Previously, he was director of the NASA Ames Research Center in Moffett Field, California (1996-2002). He was responsible for defining and executing the role of NASA Ames as a Center of Excellence for Information Technologies, including all research programs, approximately 1,500 civil servants, and 3,000 contractor employees. The center is heavily involved in supercomputing, information technologies, and aerospace and space science research.

Dr. McDonald received a D.Sc. in engineering from the University of Glasgow (Scotland) in 1985 and a B.Sc. with honors in aeronautical engineering from the University of Glasgow. He is a member of the National Academy of Engineering, a fellow of the Royal Academy of Engineering, an honorary fellow of the American Society of Mechanical Engineers and a fellow of the American Institute of Aeronautics and Astronautics.

DUNCAN T. MOORE is the chief executive officer of Infotonics Technology Center, one of five Centers of Excellence in New York State since 2002. In addition, he is the Rudolf and Hilda Kingslake professor of optical engineering and professor of biomedical engineering at the University of Rochester. From 1995 to 1997, he was dean of engineering and applied sciences at the University, and in 1996 he also served as president of the Optical Society of America.

The U.S. Senate confirmed Dr. Moore in the fall of 1997 as associate director for technology in the White House Office of Science and Technology Policy, where he served in December 2000. In this position he worked with Dr. Neal Lane, President Clinton's science adviser, to advise the president on U.S. technology policy.

Dr. Moore has extensive experience in the academic, research, business, and governmental arenas of science and technology. He is an expert in gradient-index optics, computer-aided design, and the manufacture of optical systems, as well as the founder and former president of Gradient Lens Corporation of Rochester, NY, a company that manufactures the Hawkeye boroscope.

Dr. Moore's National Academies experience includes service as a member of the Committee on Capitalizing on Science, Technology and Innovation: An Assessment of the Small Business Innovation Research Program and chair of the Panel for Physics of the Board on Assessment of National Institute of Standards and Technology Programs.

Dr. Moore holds M.S. and Ph.D. degrees in optics from the University of Rochester, and a bachelor's degree in physics from the University of Maine. He is a member of the National Academy of Engineering.

JOSEPH MORONE was named president of Albany International in August 2005 and became chief executive officer in 2006.

Prior to joining Albany International, he served as president of Bentley College for eight years and, before Bentley, as dean of the Lally School of Management and Technology at Rensselaer Polytechnic Institute. Morone's primary professional interest is in the relationship between technology and competitive advantage, particularly in the role that general business management plays in that relationship. During his tenure as president, Bentley College established itself as a national leader in integrating information technology and business education.

Prior to joining Rensselaer, Morone worked for the Keyworth Company, a consulting firm that specialized in technology management and science policy, General Electric's Corporate Research and Development, and the White House Office of Science and Technology Policy. His publications include *Winning in High-Tech Markets* (Harvard Business School Press) and *The Demise of Nuclear Power: Lessons for Democratic Control of Technology* (Yale University Press with E. Woodhouse).

Dr. Morone has a Ph.D. from Yale University in political science. He is a member of the board of directors of both the Albany International Corporation and the TransWorld Entertainment Corporation and until July 2005 served as chairman of the board of trustees at Tufts-New England Medical Center and its Floating Hospital for Children.

MARK B. MYERS is visiting executive professor in the Management Department at the Wharton Business School of the University of Pennsylvania. His research interests include identifying emerging markets and technologies to enable growth in new and existing companies, with special emphases on technology identification and selection, product development and technology competencies.

Dr. Myers retired from the Xerox Corporation at the beginning of 2000, after a 36-year career in its research and development organizations. He was the senior vice president in charge of corporate research, advanced development, systems architecture, and corporate engineering from 1992 to 2000. His responsibilities included the corporate research centers: PARC in Palo Alto, CA; Webster Center for Research & Technology near Rochester, NY; Xerox Research Centre of Canada, Mississauga, Ontario; and the Xerox Research Centre of Europe in Cambridge, UK and Grenoble, France. During this period he was a member of the senior management committee in charge of the strategic direction setting of the company.

He is chairman of the board of trustees of Earlham College and has held a visiting faculty position at the Stanford University and an adjunct position at the University of Rochester. He holds a bachelor's degree from Earlham College and a doctorate from Pennsylvania State University.

Dr. Myers served for 10 years as a member of the National Academies' Board on Science, Technology, and Economic Policy (STEP) and during that time was co-chair of its Committee on Intellectual Property Rights in the Knowledge-Based Economy. He is also a member of the STEP Committee on Measuring and Sustaining the New Economy. His other Academies experience includes service on the Board on Assessment of National Institute of Standards and Technology Programs.

NICHOLAS VONORTAS is professor of economics and international affairs at the George Washington University. He is director of both the Center for International Science and Technology Policy and of the graduate program in International Science and Technology Policy at GWU's Elliott School of International Affairs.

His teaching and research interests are in industrial organization, the economics of technological change, and science and technology policy. He specializes in strategic partnerships, innovation networks, technology transfer, technology and competition policy, and the appraisal of the economic returns of R&D programs.

Professor Vonortas is a founding member and serves on the steering committee of the Washington Research Evaluation Network (WREN). He is a research associate of CESPRI at Luigi Bocconi University in Milano, Italy, of LIEE at the National Technical University of Athens, and of MSL at the Athens University of Economics and Business in Greece. He has served as a consultant to many government agencies in the United States, the European Union, the Republic of Korea, and Japan, as well as to several international organizations on issues related to strategic partnerships, R&D program evaluation, science and technology indicators, innovation systems, and technology, competition, and intellectual property policy.

Professor Vonortas received a Ph.D. and an M.Phil. in economics from New York University, an M.A. in economic development from Leicester University (U.K.), and a B.A. in economics from the University of Athens.

TODD A. WATKINS is an associate professor of economics in the College of Business and Economics at Lehigh University and director of the Institute for the Study of Regional Political Economy. He holds Ph.D. and M.P.P. degrees from Harvard University and a B.S. from the University of Rochester.

His research and teaching focus on the intersection of technology, public policy, business, and economics. He has more than 40 related professional publications. His research on technology policy, defense industries, dual-use manufacturing, and the economics of innovation has been published in various journals, including *Science*, *Technology Review*, *IEEE Engineering Management Review*, *Defence & Peace Economics*, *Technovation*, *Governance*, and *Research Policy*. He has worked as a technology policy analyst for the Commission of the European Union and the U.S. General Accounting Office.

Prior to his graduate studies, he was a practicing engineer, working in optical design and manufacturing for the Eastman Kodak Company. He has been a consultant to the U.S. Department of Commerce's Advanced Technology Program, the U.S. Congressional Office of Technology Assessment, Arthur D. Little, the Semiconductor Research Corporation, and was a research team member of the Massachusetts Institute of Technology's Lean Aircraft Initiative, a consortium of 20 major aerospace companies. He has been a visiting scholar at the Centre for Defence Economics, University of York, England, a center associate of the Center for Trade & Commercial Diplomacy, Monterey Institute of International Studies, and a research fellow in the Center for Science and International Affairs, Harvard University.

DEBORAH L. WINCE-SMITH has been president of the Council on Competitiveness since December 2001. She is an internationally recognized expert on science and technology policy, innovation strategy, technology commercialization, and global competition, as well as a frequent speaker and author on these topics. Ms. Wince-Smith serves on boards, committees and policy councils of numerous high-technology companies, national nonprofits, and other organizations, including the Woodrow Wilson Center, the University of California President's Council on National Laboratories, the University of Pennsylvania Museum of Archaeology and Anthropology, the National Inventors Hall of Fame, the Pilgrims of the United States, and the International Women's Forum. Most recently, Ms. Wince-Smith was appointed by the U.S. Department of Energy to be a member of the Secretary's Task Force on the Future of Science Programs.

Prior to joining the Council on Competitiveness as a senior fellow in 1993, Ms. Wince-Smith was the first assistant secretary for technology policy in the U.S. Department of Commerce. Previously, she served as assistant director for international affairs and competitiveness in the White House Office of Science and Technology Policy and as a program manager at the National Science Foundation from 1976 to 1984.

Trained as a classical archaeologist, Ms. Wince-Smith graduated phi beta kappa and magna cum laude from Vassar College, received her master's degree from King's College, Cambridge University, and conducted fieldwork in Greece.

STEPHEN A. MERRILL (Project Director) has been executive director of the National Academies' Board on Science, Technology, and Economic Policy (STEP) since its formation in 1991. He has directed several STEP projects in the areas of intellectual property, technical standards, taxation, human resources, and statistical as well as research and development policies. For his work on the report *A Patent System for the 21st Century* (2004) he was named one of the 50 most influential people worldwide in the intellectual property field by *Managing Intellectual Property* magazine and was awarded the Academies' Distinguished Service Award in 2005.

Prior to his appointment to the Academies' staff, Dr. Merrill was a fellow in international business at the Center for Strategic and International Studies and 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 the semiconductor and biotechnology industries. He holds degrees in political science from Yale (M.A., Ph.D.), Oxford (M.Phil.), and Columbia (B.A.) Universities.