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EXPANDING FLIGHT RESEARCH

CAPABILITIES, NEEDS, AND MANAGEMENT OPTIONS FOR NASA'S AERONAUTICS RESEARCH MISSION DIRECTORATE

RAND CORPORATION

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Front cover: This schlieren image dramatically displays the shock wave of a supersonic jet flying over the Mojave Desert. Researchers used NASA-developed image processing software to remove the desert background, then combined and averaged multiple frames to produce a clear picture of the shock waves.

Back cover: This schlieren image of shock waves created by a T-38C in supersonic flight was captured using the sun's edge as a light source and then processed using NASA-developed code.

Preface

The Aeronautics Research Mission Directorate (ARMD) of the National Aeronautics and Space Administration (NASA) is working to expand flight research activities, with the objective of rapidly advancing new aeronautic concepts by increasing their maturity and demonstrating their practical utility. To inform this strategic shift, NASA ARMD asked the RAND Corporation to assess its flight research needs and capabilities, identify any gaps or excess, and develop management options for expanding flight research. This report summarizes the results of RAND's effort, presenting options and recommendations for ARMD.

Beyond ARMD leadership, this report should be of interest to those responsible for managing NASA flight research infrastructure and capabilities, aeronautics researchers, and the broader oversight community in the Office of Management and Budget, the Office of Science and Technology Policy, and Congress.

Information for this study was collected from October 2014 through February 2016. This effort was also informed by RAND's strategic assessments of national needs and capabilities for NASA's wind tunnels and propulsion-test facilities:

- Philip S. Anton, Eugene C. Gritton, Richard Mesic, et al., *Wind Tunnel and Propulsion Test Facilities: An Assessment of NASA's Capabilities to Serve National Needs*, Santa Monica, Calif.: RAND Corporation, MG-178-NASA/OSD, 2004. www.rand.org/pubs/monographs/MG178
- Philip S. Anton, Dana J. Johnson, Michael Block, et al., *Wind Tunnel and Propulsion Test Facilities: Supporting Analyses to an Assessment of NASA's Capabilities to Serve National Needs*, Santa Monica, Calif.: RAND Corporation, TR-134-NASA/OSD, 2004. www.rand.org/pubs/technical_reports/TR134
- Philip S. Anton, Raj Raman, Jan Osburg, and James G. Kallimani, *An Update of the Nation's Long-Term Strategic Needs for NASA's Aeronautics Test Facilities*, Santa Monica, Calif.: RAND Corporation, DB-553-NASA/OSTP, 2009. www.rand.org/pubs/documented_briefings/DB553
- Thomas Light, Chad J. R. Ohlandt, and Jan Osburg, *Pricing Strategies for NASA Wind-Tunnel Facilities*, Santa Monica, Calif.: RAND Corporation, TR-999-NASA, 2011. www.rand.org/pubs/technical_reports/TR999

It also builds on RAND research for ARMD on aeronautics needs and strategy:

- Philip S. Anton, Liisa Ecola, James G. Kallimani, et al., *Advancing Aeronautics: A Decision Framework for Selecting Research Agendas*, Santa Monica, Calif.: RAND Corporation, MG-997-NASA, 2011. www.rand.org/pubs/monographs/MG997

RAND Science, Technology, and Policy Program

The research reported here was conducted in the RAND Science, Technology, and Policy program, which focuses primarily on the role of scientific development and technological innovation in human behavior, global and regional decisionmaking as it relates to science and technology, and the concurrent effects that science and technology have on policy analysis and policy choices. The program covers such topics as space exploration, information and telecommunication technologies, and nano- and biotechnologies. Program research is supported by government agencies, foundations, and the private sector.

This program is part of RAND Justice, Infrastructure, and Environment, a division of the RAND Corporation dedicated to improving policy- and decisionmaking in a wide range of policy domains, including civil and criminal justice, infrastructure protection and homeland security, transportation and energy policy, and environmental and natural resource policy.

Questions or comments about this report should be sent to the project leader, Jan Osburg (Jan_Osburg@rand.org). For more information about the Science, Technology, and Policy program, see www.rand.org/jie/stp or contact the director at stp@rand.org.

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Summary

The Aeronautics Research Mission Directorate (ARMD) of the National Aeronautics and Space Administration (NASA) is pursuing a strategic initiative to revitalize and expand its flight research activities, with the objective of rapidly advancing new aeronautic concepts by increasing their maturity and demonstrating their practical utility.[1] These efforts build on existing activities, including fundamental research, ground-based testing, and flight research and testing of recent ARMD concepts. The initiative is part of ARMD's new Strategic Implementation Plan (SIP), which establishes aeronautics research thrust areas for the next ten years.[2] In light of this strategic initiative, ARMD asked the RAND Corporation to examine gaps and other needs in flight research capabilities, identify ways in which NASA can efficiently fill those needs (especially, but not limited to, external partnerships), and identify strategic management options (MOs) that can improve efficiency and expand flight research both generally and in specific areas of the SIP.

Note that the ten-year study horizon introduces uncertainties and unknowns that result in less specificity in our findings. On the demand side, specific research activities and their timing cannot be predicted with accuracy over such a long term. On the supply side, while NASA's flight research activity is benefiting from recent significant increases in ARMD budgets that are expected to persist over the foreseeable future, budget levels over the next ten years similarly cannot be predicted precisely.

To address this challenge, we developed high-level needs projections for three different demand futures (reduced, steady-state, and increased demand) and, based

1 Note that although the terms "flight test" and "flight research" are often used interchangeably, there is a difference: *flight test* generally refers to testing or validating an existing vehicle or system, or to a specific sortie of an aircraft in support of a campaign, while *flight research* also includes flight-based efforts to advance the understanding of fundamental aeronautical principles. Thus, in the research, development, test, and evaluation continuum, flight research is closer to the research side, and flight tests closer to the evaluation side (National Research Council, 2012). NASA mostly engages in research and development, rather than testing and evaluation; thus, *flight research* is used throughout this report unless the use of *flight test* is specifically indicated.

2 ARMD's strategic thrusts are: (1) Safe, Efficient Growth in Global Operations, (2) Innovation in Commercial Supersonic Aircraft, (3) Ultra-Efficient Commercial Vehicles, (4) Transition to Low-Carbon Propulsion, (5) Real-Time System-Wide Safety Assurance, and (6) Assured Autonomy for Aviation Transformation (NASA, 2015c).

thereon, developed broader strategic options that are useful regardless of the level of ARMD's budget and the specific unfolding of NASA's SIP.

NASA's Flight Research Infrastructure Status

NASA has strong flight research capabilities in the areas of workforce, test ranges, test airspace, and chase aircraft that support ARMD's strategic priorities in subsonic fixed-wing and vertical lift, commercial supersonic aircraft, low-carbon emission propulsion, safety, airspace operations, and unmanned vehicle operations and autonomy. NASA has good capabilities in subsonic fixed-wing and supersonic modifiable testbed aircraft. While gaps exist in other areas (such as modifiable rotorcraft and large-scale transport testbed aircraft), filling these gaps would involve the acquisition of readily available vehicles in the marketplace; thus, they are a budget and planning challenge rather than a longer-term vehicle research, development, and production challenge. Finally, sub- and full-scale experimental aircraft gaps abound, but these cannot be acquired before the specific research projects are planned and developed, thus requiring a stable strategic planning environment.

The Space of Management Options for Facilitating Flight Research

To review as broad a set of MOs as possible, we first listed the range of approaches that NASA might take to increase flight research:

1. increasing ARMD's overall budget
2. increasing the portion of the ARMD budget that is spent on flight research
3. Making the ARMD budget for flight research go further by:
   - improving the efficiency of NASA's flight research enterprise
   - taking different approaches to adjusting flight research infrastructure
   - increasing cost sharing
4. lowering barriers to flight research
5. better aligning flight research capabilities with research needs.

The first three approaches address supply-side improvements, enabling more flight research through increased funding and/or increased efficiencies. The last two approaches cover the demand side: making flight research more attractive to researchers.

We then identified and assessed 20 MOs within this option space. Prioritization led to 15 promising MOs in five categories (see Table S.1). All of these options are compatible with each other, and several combinations can be expected to yield synergistic benefits.

Table S.1
Top Management Options Identified

Category	Management Option	
I: Improve Strategic Planning	MO-01	Planning integration
	MO-02[a]	Strategic investment
	MO-03[a]	Acquire-at-need
	MO-04	Increase budget certainty
Ii: Partnering	MO-05	Increase cooperation
	MO-06[a]	Increase partnering
Iii: Refine Research Scope	MO-07	Space/military tie-in
	MO-08[a]	Annual needs survey
Iv: Identify and Implement Efficiency Improvements	MO-09	Cross-center management
	MO-10	Balance risks
	MO-11[a]	Adjust number of chase planes
	MO-12	Voucher system
	MO-13	Streamline process
	MO-14	Improve data access
V: Advocate for additional funding	MO-15	Return-on-investment analysis

[a] These MOs involve NASA organizations beyond ARMD.

While some of these options are rather obvious and some are already being pursued by ARMD, it was useful to review the entire space of options for this effort. We also found that these options should be useful regardless of whether ARMD's future budgets increase further, level out, or drop.

Further prioritization resulted in 13 recommended options for ARMD to consider. This set of options is explained briefly in this summary. All 15 options are discussed in the report at a level of detail meant to help the sponsor identify preferred options for further consideration and in-depth analysis.

I. Improve Strategic Planning

Continued emphasis on strategic planning can focus project attention on flight research, lead to strategic investments and management of flight research infrastructure, and generate options for filling gaps when needed. It also helps with prioritization of projects and their budgets to distinguish projects (and infrastructure investments) with high budgetary confidence from those that fall at the margins and thus should plan on contingencies if funding becomes unstable.

Prioritize investments in strategic capabilities (MO-02). One way of improving the efficiency of flight research is ensuring that high-priority infrastructure capabilities are available and modernized to facilitate progress. Given the extensive breadth of ARMD's SIP, an explicit prioritization of capabilities (as later described in MO-04) could inform possible infrastructure investments—as well as management dynamics, such as planned mothball/reconstitution cycles for intermittently needed capabilities or upgrades to more-modern capabilities during periods of low to no utilization. Our review of general infrastructure indicates that most areas are covered by some kind of NASA asset, but some general gaps exist (see our analysis of capability gaps and excess in Chapter Two in the main report). Moreover, detailed needs will arise as specific, detailed plans for research projects are developed. This will include both the designs and alternatives for X-planes, as well as needed component upgrades to existing assets. The report uses the supersonic aircraft fleet as an example to illustrate this MO.

Acquire-at-need instead of sustaining assets when no utilization is planned for long periods (MO-03). In some cases, flight research aircraft can be readily acquired at need in the open marketplace with relatively little lead time (e.g., one to three years to acquire and modify the aircraft and train the workforce). This option could be considered when needs are strongly intermittent, when an identified capability gap does not need to be filled in the immediate future, or when the time frame for need cannot be determined.

Increase research project budget planning certainty to three to five years (MO-04). One of the most valuable things ARMD leadership can do to improve flight research is stabilize planning three to five years out for research managers. This involves two key elements: (1) continuing to lengthen planning horizons (as in the current SIP activities) and (2) prioritizing activities in the plan. Stable plans will help not only research planning but also infrastructure planning and investments. The latter is important to prepare capabilities efficiently within the given required lead times, while avoiding waste from unused capabilities or capacity. While Congress controls ARMD's yearly budget levels, much of the uncertainty lies at the margins—not in the bulk of the budget—and ARMD has significant latitude in prioritizing research within its budget. Thus, if projects and technical challenges were explicitly prioritized, then ARMD could provide reasonably high confidence to the highest-priority projects and allow their project leaders (and their associated infrastructure providers) to maximize efficiency through anticipated stable plans and fairly certain funding streams. For example, priority projects funded with the first $400 million per year in ARMD's budget could be designated "highly confident" and thus project leaders could optimize their plans based on the expectation of stable funding, rather than having to plan for contingencies. Projects funded with the next $100 million could be designated as "confident" and managers could prepare in similar fashion. On the other hand, projects for which the funds are taken from beyond the first $500 million of the ARMD budget would know that their budgets are less certain; thus, they would need to plan for contingencies to handle budgetary uncertainties over the next few years. It should be noted that these priorities are separate from the normal uncertainty of research progress and associated cuts based on project performance.

II. Partnering

ARMD has successfully utilized partnerships and cooperative research in the past and plans to continue doing so. Partnerships with other government agencies, industry, academia, and international organizations that have flight research capabilities of interest continue to be an important option. Partnerships can extend ARMD research by leveraging external capabilities, reducing the need for NASA ownership of those capabilities, and promoting technology transfer and application of research.

Increase cooperative research (MO-05). Fostering collaboration and cooperation with outside organizations (other government agencies, industry, academia) that are interested in performing flight research using NASA capabilities, usually on a cost-reimbursable basis, remains a viable option in certain circumstances. Increasing the quantity and quality of cooperative efforts requires management attention to several issues: an organizational culture and workforce that can provide good customer service; proper sharing of credit with collaboration partners, including through proper planning of any outreach activities and publications; and making sure research that is brought in is in general alignment with NASA's mission, while avoiding a "what's in it for NASA" mindset.

Increase partnering (MO-06). Partnerships and external reliance continue to be viable options for NASA to consider. We identified a number of external flight research aircraft that could be leveraged through a partnership (see Chapter Two of the main report). Working with partners can have limitations, however. The report discusses examples of, and challenges with, partnerships with other government agencies, U.S. companies, academia, and foreign flight research organizations.

III. Refine the Scope of ARMD Research

Refining the scope of the research and continually aligning it with the needs of the community can strengthen the support for flight research.

Perform an annual survey of requirements, needs, and ideas (MO-08). Being more proactive about identifying user ideas, needs, and priorities could help alert ARMD to changes in demand across the U.S. flight research community, facilitate strategic management of flight research, and contribute to increasing the base of potential users. A well-publicized annual survey could be instituted, complemented by less frequent long-term examinations like the Decadal Surveys compiled by the National Academies of Science. Leadership prioritization is key to planning, integrating, and scoping the results.

IV. Identify and Implement Efficiency Improvements

Regardless of whether ARMD's budget increases or not, improving the efficiency of available dollars is always useful. NASA headquarters, NASA centers, and ARMD have already been working on increasing the efficiency of NASA's flight research enterprise, but we identified several additional options for consideration. Note that some of these options cannot be implemented by ARMD alone because they affect NASA center and NASA headquarters assets and roles. Beyond raising operational efficiencies, flight research also may be facilitated by lowering the barriers to access and thus encouraging researchers to make increased use of flight research capabilities.

Institute cross-center matrix management of flight research capabilities and partnership outreach (MO-09). Significant effort and progress has been made at NASA to increase cooperation between—and joint participation among—NASA flight operation organizations. A new cross-center matrix management of flight research and operations centers could facilitate further cooperation and coordination among these organizations. Under such a structure, the flight operations organization at each center would be part of a single NASA management organization. They would be matrixed to support local research at the center where they reside, as well as needs and projects based at other centers. Staff would work to facilitate access to any NASA flight research capability regardless of location, serving as a one-stop-shop to facilitate knowledge of and access to all NASA capabilities, introducing added value to the local researcher. Perhaps just as important, the matrixed organization also could serve as the central NASA organization responsible for flight research partnership information, outreach, and management. This function would facilitate tracking the capabilities of external entities, coordinate outreach, simplify contacting and referral, and facilitate research program access and utilization of external capabilities and partnerships while providing coordinated advice on issues such as intellectual property decisions and international policies.

Explicitly balance and manage risks (MO-10). Flight research is subject to interacting execution risks affecting cost and schedules. Research may be delayed or even prevented by capability gaps, capacity limits, or incentive mismatches between capability providers and capability users. Inefficiencies resulting from fluctuating demand that lead to unutilized or underutilized capabilities can adversely affect program budgets and lead to delays—even collateral effects on other programs. Explicitly and effectively balancing such risks across all elements involved in flight research (aircraft, airspace, ranges, ground infrastructure, and workforce) in a way that is robust with respect to uncertainties in strategic planning, future budgets, and capability availability and demand, promises to increase flight research efficiency. Such an effort would benefit from making explicit the key dependencies and risks involved in flight research management, and would have to be regularly updated and adapted to changing circumstances. A number of risk-management approaches could be employed to explicitly consider risks and their consequences in ARMD's strategic planning and decisionmaking. Some approaches use portfolio simulations to recommend sets of investment portfolios that maximize utility relative to larger strategic goals given the uncertainty of project success (Davis, 2008; Chow, 2011). Other approaches consider explicit risk trade-offs, such as examining the effect of reduced backup aircraft (and thus reduced fleet costs) in exchange for schedule risk on research projects (see MO-11); such trade-offs may be considered in times of restricted budgetary resources. In addition, the budgetary prioritization option (MO-04) would identify projects that are at the margins and thus have higher funding risks. Explicit identification of those risks should lead those projects to develop risk-mitigation plans for how they would handle budgetary instability and the effect of that instability on infrastructure investments needed for their research.

Trade schedule risk for cost by adjusting the number of backup aircraft (MO-11). Another option is to allow for increased schedule risk in exchange for cost reductions through reduced infrastructure redundancy—namely in backup chase aircraft. The report describes a probabilistic approach that quantifies the cost and schedule trade-off implications from reducing backup aircraft by estimating the probability of aircraft unavailability as backup aircraft are reduced.

Institute a voucher system for short, exploratory flight research (MO-12). Allocating a modest amount (tens) of free-of-charge flight research hours for exploratory flight research efforts could encourage more researchers to test innovative ideas and investigate new concepts. Flight hours for this could be combined with those needed for mandatory pilot proficiency training to reduce the amount of additional funding required. This would make good use of capability availabilities between major scheduled projects and could be a mechanism for more-transparent allocation of research opportunities on pilot proficiency flights that are already paid for. Such an effort also could be expanded to include researchers outside NASA (e.g., in academia) who may have concepts that would benefit from small amounts of flight research but who do not have sufficient funding for flight research (e.g., in a similar way that NASA allocates supercomputing time to researchers). For example, many academics use RC aircraft to test aeronautics concepts; a voucher system would allow them to scale their concept to large unmanned aircraft systems or manned aircraft and conduct preliminary tests in just a few flight hours, gaining insights that could help determine whether the concepts should be investigated further. If done right, such seed support would facilitate innovative flight research and could boost aeronautics progress.

Streamline the process that researchers must use to obtain flight research capabilities (MO-13). More-transparent and more-responsive processes for planning and scheduling flight research activities can draw more researchers to flight research—possibly while reducing overhead. This could include identifying and eliminating unnecessary procedural hurdles and establishing a centralized web portal for identifying and reserving flight test capabilities. It could also identify staff who can help researchers navigate the required processes and paperwork (for example, the matrixed organization idea outlined in MO-09). Furthermore, outfitting additional aircraft with standardized payload interfaces could facilitate integration of payloads. Finally, an annual flight research outreach event could be established to introduce researchers to flight research capabilities across NASA, which would also help to build the awareness needed to fully implement MO-01.

Improve access to flight research data for researchers (MO-14). Currently, NASA flight research data are neither centrally stored nor readily accessible to the U.S. aeronautics research community outside those directly involved in a specific research project. Creating an obsolescence-proof storage and retrieval system for such data would increase the value extracted from existing flight research, inspire new research ideas and associated flight research requirements, and help avoid redundant testing. NASA's Chief Information Officer is already developing cloud standards that can handle export-controlled data while facilitating secure access and efficient management and scalability.

V. Advocate for Additional Funding

Finally, the most straightforward approach to meeting ARMD's goal of increasing flight research is to increase the overall ARMD budget and, with that, the funding that can be made available for flight research. While NASA has made progress in this area (e.g., recent congressional budgetary increases in the $60 million–100 million range and the President's fiscal 2017 budget request proposing dramatic funding increases for ARMD), the following MO could further enable that progress.

Demonstrate return on investment by articulating benefits, especially in monetary terms, to explain their value (MO-15). Whenever possible, NASA should continue to explain potential benefits in both domain and monetary terms. NASA funding ultimately depends on convincing external decisionmakers that the taxpayers' money is put to good use. Unfortunately, benefits from aeronautics are hard for nonspecialists to put in perspective and compare with costs when expressed in direct terms. For example, four billion gallons in saved jet fuel (NASA, 2014b) could have been converted to a dollar value (i.e., $11.4 billion at the 2014 fuel cost of $2.85 per gallon; Bureau of Transportation Statistics, 2015). Also, eliminating 43 million tons of carbon dioxide (NASA, 2014b) represents $1.8 billion in social costs using published government guidelines for the social cost of carbon dioxide (Environmental Protection Agency, 2015). Presenting both the explanation of what the benefits are (eliminating 43 million tons of carbon dioxide) plus the monetary value ($1.8 billion) better informs nonspecialists of the costs and benefits of NASA's research.

Conclusion

This study has generated a set of MOs and developed related courses of action that could facilitate ARMD's desired increase in flight research and help address related challenges.

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Any remaining errors are strictly the responsibility of the authors.

Abbreviations

AC	aircraft
ACCESS	Alternative Fuel Effects on Contrails and Cruise Emissions
ACTE	adaptive conformal trailing edge
AFB	Air Force Base
AFFTC	Air Force Flight Test Center
AFRC	Armstrong Flight Research Center
AFRL	Air Force Research Laboratory
AMD	Aircraft Management Division
ARC	Ames Research Center
ARMD	Aeronautics Research Mission Directorate
ATM	Air Traffic Management
AWS	Amazon Web Services
BCA	benefit-cost analysis
BLI	boundary layer ingestion
CAS	commercial aviation services
CFD	computational fluid dynamics
CIO	Chief Information Officer
CRADA	cooperative research and development agreement
DATR	Dryden Aeronautical Test Range
DLR	Deutsches Zentrum für Luft– und Raumfahrt
DoD	U.S. Department of Defense
ERA	Environmentally Responsible Aviation
EU	European Union
FAA	Federal Aviation Administration
FEM	finite element method
FY	fiscal year

GOCO	government-owned, contractor-operated
GRC	Glenn Research Center
HEOMD	Human Exploration and Operations Mission Directorate
HQ	headquarters
IP	intellectual property
ITAR	International Traffic in Arms Regulations
JAXA	Japan Aerospace Exploration Agency
JSC	Johnson Space Center
KSC	Kennedy Space Center
LaRC	Langley Research Center
LBFD	Low-Boom Flight Demonstrator
M	Mach
M&S	modeling and simulation
MO	management option
MOD	United Kingdom Ministry of Defence
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NRC	National Research Council
NRC-Canada	National Research Council–Canada
NSTC	National Science and Technology Council
OMB	Office of Management and Budget
OSTP	Office of Science and Technology Policy
P&W	Pratt and Whitney
R&D	research and development
RDT&E	research, development, test, and evaluation
ROI	return on investment
SAMO	Support Aircraft and Maintenance Operations
SIP	Strategic Implementation Plan
SMD	Science Mission Directorate
SME	subject-matter expert
SOFIA	Stratospheric Observatory for Infrared Astronomy
SOFRS	Science Operations Flight Request System
T&E	test and evaluation
TRL	technology readiness level

UAS	unmanned aircraft systems
UHBR	ultra-high bypass ratio
UK	United Kingdom
USAF	U.S. Air Force
WFF	Wallops Flight Facility

CHAPTER ONE

Introduction

Flight research, flight testing, and flight safety analysis are essential components of advancing civil and military air transportation the United States.[1] Since its inception in 1958, the National Aeronautics and Space Administration (NASA) has made significant progress in these areas. NASA's Aeronautics Research Mission Directorate (ARMD) and its predecessor organizations have directly and indirectly improved the safety, reliability, and efficiency of flight. Many of the flight operations procedures and technologies that travelers and pilots take for granted today are based on fundamental breakthroughs and early demonstrations by NASA (National Research Council [NRC], 2012).

ARMD leadership recognizes the importance of validating and expanding on model- and laboratory-based research results in realistic flight conditions because flight research is required to make theoretical concepts tested in computer simulations and ground-test facilities ready for practical application. Also, some concepts cannot be physically or cost-effectively tested in simulations or ground-test facilities. Additionally, there may be opportunities to advance the aeronautics field as a whole if exploratory flight research is conducted early on in a project's conception, rather than as only a final proof of the results of theoretical work and ground testing.

ARMD is therefore pursuing a strategic initiative to revitalize and expand its flight research activities, with the objective of rapidly advancing new aeronautic concepts by increasing their maturity and demonstrating their potential. The initiative builds on other efforts, including a range of fundamental research, ground-based testing, and flight research and testing of recent ARMD concepts, and is part of ARMD's new Strategic Implementation Plan (SIP), which establishes research thrust areas for the next ten years (NASA, 2015c; see Chapter Two). To help inform this strategic shift, ARMD asked the

[1] Note that although the terms "flight test" and "flight research" are often used interchangeably, there is a difference: *flight test* generally refers to testing or validating an existing vehicle or system, or to a specific sortie of an aircraft in support of a campaign, while *flight research* also includes flight-based efforts to advance the understanding of fundamental aeronautical principles. Thus, in the research, development, test, and evaluation (RDT&E) continuum, flight research is closer to the research side, and flight tests closer to the evaluation side (National Research Council [NRC], 2012). NASA mostly engages in research and development, rather than testing and evaluation; thus, *flight research* is used throughout this report unless the use of *flight test* is specifically indicated.

RAND Corporation to assess its flight research and flight test needs and related capabilities, identifying gaps and management options (MOs) that support evolving ARMD and national requirements for the efficient RDT&E of aeronautical concepts, systems, and vehicles over the next ten years. This effort was informed by approaches that RAND researchers took to assess the strategic national needs and capabilities for NASA's wind tunnels and propulsion-test facilities (Anton, Gritton, et al., 2004a; Anton, Johnson, et al., 2004b; Anton, Raman, et al., 2009; Light et al., 2011). It builds on RAND research for ARMD on flight research, as well as on aeronautics needs and strategy (e.g., Anton, Ecola, et al., 2011).

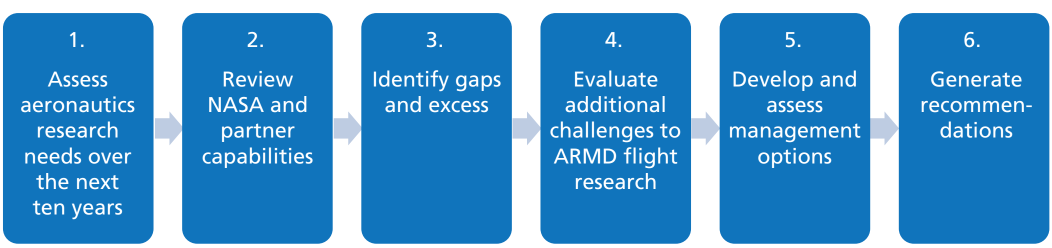
Study Approach and Scope

Our study started with an assessment of ARMD's aeronautics research needs over the coming decade as expressed in strategic plans. We also reviewed flight research capabilities available to ARMD at NASA centers and at external organizations. This enabled us to identify any gaps and excess. We also identified issues not directly related to needs and capabilities that nevertheless pose challenges to ARMD. Based on this work, we identified a preliminary list of MOs, which were then systematically assessed by the RAND team and reviewed by external subject-matter experts (SMEs), leading to our final list of recommendations. Figure 1.1 illustrates this process.

The first and second steps of our approach required an extensive literature review, including ARMD program planning documents and reports from the National Academies. We also collected extensive data from ARMD leadership and researchers as well as from other NASA center and headquarters (HQ) staff. We also gathered feedback on our initial needs analysis through semistructured, nonattribution discussions with senior SMEs external to NASA and RAND, covering areas of NASA and industry aeronautics management, flight research, flight testing, and aeronautics research.

Note that the ten-year study horizon introduces uncertainties and unknowns that result in less specificity in our findings. On the demand side, specific research activi-

Figure 1.1
ARMD Flight Research Management Options Study Plan



RAND *RR1361-1.1*

ties and their timing cannot be predicted with accuracy over such a long term. On the supply side, while NASA's flight research activity is benefiting from recent significant increases in ARMD budgets that are expected to persist over the foreseeable future, budget levels over the next ten years also cannot be predicted precisely.

Despite these limitations, by using a futures-based approach, we were able to identify broader strategic direction, needed capabilities, and MOs.

Aeronautics Research Needs over the Next Ten Years

The 2015 ARMD SIP provided the foundation for our needs assessment. The SIP outlines six "strategic thrusts" that were developed by ARMD based on NASA's strategic planning and analysis of strategic trends both in U.S. aeronautics and in global economic developments. The strategic thrusts are:

1. **Safe, Efficient Growth in Global Operations:** Enable implementation of the NextGen air transportation system, and develop technologies to substantially reduce aircraft safety risks.
2. **Innovation in Commercial Supersonic Aircraft:** Achieve a low-boom standard.
3. **Ultra-Efficient Commercial Vehicles:** Pioneer technologies for big leaps in efficiency and environmental performance.
4. **Transition to Low-Carbon Propulsion:** Characterize drop-in alternative fuels and pioneer low-carbon propulsion technology.
5. **Real-Time System-Wide Safety Assurance:** Develop an integrated prototype of a real-time safety monitoring and assurance system.
6. **Assured Autonomy for Aviation Transformation:** Develop high-impact aviation autonomy applications (NASA, 2015c).

To help understand other uses for NASA flight research capabilities and other possible research needs that might arise as NASA's and ARMD's strategic plans evolve over the next decade, we also considered the potential contributions of aeronautics research to other NASA missions and associated research, from Earth science to space exploration, and, for additional context, included national needs as designated by governmental institutions (e.g., the U.S. Department of Defense [DoD] and the Federal Aviation Administration [FAA]), the commercial sector, and academia. Based on this, we developed high-level needs projections for three different demand futures: reduced, steady-state, and increased.

It is important to note that detailed research plans do not extend out ten years because they naturally depend on research results (successes and failures) as well as the inevitable evolution of strategic plans and budgets through different presidential administrations and congressional sessions. Research program planning in response to ARMD's new SIP was under way during this study, and even though further details have been emerging recently, these dynamics will still lead to uncertainties and change. Also, while the SIP provides a useful map of what ARMD wants to do, there is additional uncertainty because the range of potential research under the SIP is larger than ARMD's budget affords, even with the significant increases in aeronautics funding evident in the fiscal year (FY) 2017 presidential budget proposal (Office of Management and Budget [OMB], 2016). Therefore, as in prior work (e.g., Anton, Gritton, et al., 2004a; Anton, Johnson, et al., 2004b), we examined the conceptual range of needs and capabilities, rather than specific details (e.g., the predicted number of flight hours needed for specific aircraft out to ten years). Also, many of our MOs aim to better manage these dynamics and uncertainties, and help make NASA's flight research enterprise more efficient no matter the funding levels.

NASA and Partner Capabilities

Flight research includes the investigation of aeronautical principles, concepts, and vehicles, as well as the execution of scientific research from aerial platforms. While NASA conducts both, ARMD research focuses on the former: aeronautics-related RDT&E, which is further divided into the research and development (R&D) of new concepts or designs and the test and evaluation (T&E) of systems heading to production or upgrades to operating aircraft. As a research organization, NASA ARMD does far more R&D than T&E. That is not to say that NASA flight test capabilities are not used for T&E—just that ARMD work tends to focus on the early R&D stages.

Organizationally, flight research exists across NASA mission directorates, across the U.S. government (including DoD and FAA), in academia, in commercial efforts to develop and certify aircraft, and in foreign equivalents. While our research efforts strove to at least be aware of all the above, our statement of work focuses on the flight research needs and capabilities most relevant to ARMD.

Flight research capabilities are defined in this study as aircraft used for aeronautics R&D, plus associated ground-based capabilities directly related to their operations and safety. We included five general categories: *workforce, test ranges, airspace, chase aircraft,* and *research aircraft*. Since our analysis focused on strategic concerns, we considered only those capabilities that met NASA's three-part definition of a "Capital Asset" (NASA, 2011b):

1. acquisition cost of $100,000[2] or more (in acquisition-year dollars)
2. estimated useful life of more than two years
3. current or planned alternative future use on another project with a separate objective.

[2] NASA's "Capital Asset" definition changed to $500,000 acquisition cost during the period of performance of this study; however, we decided to maintain the $100,000 level in order to capture as many assets as possible; otherwise, the smallest of the General Aviation–type aircraft would have been excluded.

Note that most of the more than 100 unmanned aircraft systems (UAS) currently operated by NASA did not meet all three parts of this threshold (NASA, 2015a, p. 48) and thus are not included in our analysis. However, UAS clearly can play a significant role in flight research, be it as subscale integrated test vehicles, as experiment carriers, or potentially as additional chase platforms.

Capability Gaps and Excess

We compared the needs with the capabilities as a way to identify any gaps or excess. Given the uncertainties already outlined, this gap analysis was at the level of research domains in the SIP thrust areas mapped against the five areas of flight research capabilities to identify general categories of flight capabilities that are either lacking or unneeded. Specific capacity levels,[3] annual flight hours, and detailed aircraft custom features for specific research projects cannot be reliably forecast and assessed over a ten-year horizon.

Additional Challenges to ARMD Flight Research

To prepare for the analysis of practical MOs, we examined organizational and other challenges facing flight research at NASA, and reviewed how they affect flight research capabilities, assets, and the workforce. For this step, we reviewed NASA documentation and received additional information from our SMEs.

Develop and Assess Management Options

The gap analysis and assessment of additional challenges led us to develop MOs to improve flight research at ARMD, resulting in 15 options grouped into five areas. We systematically assessed their advantages and disadvantages regarding their effect on time, cost, and risk. At NASA's request, one specific option ("Increase Partnering") was analyzed in further detail, using four scenarios that represent past and potential future ARMD flight research projects. Our panel of senior SMEs provided further review and feedback on these options on a nonattribution basis.

Recommendations

Based on the outcomes of the above efforts, we compiled a set of specific recommendations for ARMD leadership that will help increase both the quantity and quality of flight research and more efficiently manage flight research capabilities. While some of these recommendations can be implemented by ARMD, the implementation of others would affect areas outside ARMD and thus would have to be adopted at the NASA level.

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[3] We distinguish between *capability* and *capacity*, with capability being if NASA can perform the work and capacity being how much of that work can NASA accomplish.

Caveats and Limitations

This section summarizes the limitations affecting this study and discusses some additional caveats.

To keep the scope of this study manageable, we only included flight research capabilities in this assessment that met NASA's "Capital Asset" definition (as already explained). Most of the many UAS that have been acquired by NASA centers over the past several years do not meet that threshold and thus were not taken into account, despite the increasingly important role of UAS in flight research. We would certainly recommend that ARMD study this topic in the near future.

To focus our limited resources on the most-relevant work, we also did not include international flight research capabilities from countries such as China and Russia, with which close collaboration in aeronautics research is less likely in the foreseeable future.

The timing of this study imposed certain limitations as well. At the time of the kick-off meeting, ARMD had not yet published its SIP nor had it finalized its internal reorganization. Therefore, during most of the study period, ARMD programs, projects, technical challenges, and underlying research activities were still working on revising their research plans accordingly. Furthermore, the increase in future aeronautics funding only became apparent toward the end of the study period, with the FY 2017 presidential budget proposal (OMB, 2016)—which shows the clearest indication of increased funding—being published after the draft of this report had already been written. We nevertheless incorporated this late-breaking information into our findings and recommendations.

Finally (and again, as previously outlined), we did not attempt to make a detailed, quantitative prediction of flight research needs and capabilities for the coming decade, due to the vagaries of the environment in which NASA and ARMD operate. However, through our futures-based approach, we nevertheless captured the expected range of developments in a way that allowed us to develop a robust set of recommendations.

Organization of This Report

The remainder of this report is organized as follows: Chapter Two covers our assessment of flight research needs and capabilities applicable to ARMD flight research. Subsequently, it presents the results of our gap analysis. Chapter Three discusses other challenges to increasing flight research. Chapters Four and Five build on the information in Chapters Two and Three, outlining the set of MOs that address these challenges, and discussing and assessing their potential advantages and disadvantages. Finally, Chapter Six concludes with a presentation of a prioritized subset of recommended MOs for NASA. Appendix A provides in-depth discussion of specific partnering opportunities with external organizations, and of limitations and practical considerations related to partnering; Appendix B includes further discussion of MO-09, including implementation concepts and considerations.

CHAPTER TWO

NASA ARMD Flight Research Needs, Capabilities, and Strategic Gaps

This chapter presents our analysis of NASA's capability to support flight research requirements in SIP-appropriate areas. There are three sections in this chapter. First, we estimate aeronautics flight research needs for the next ten years based on existing, planned, and conceptualized aeronautical programs, projects, and technical challenges. We also evaluate the potential impact of modeling and simulation (M&S) capability developments on flight research demands because M&S tools, flight research, and ground-based testing form the triad of aeronautics research and experimentation tools. Based on this, we generate a set of three estimates for future needs, representing steady, reduced, and increased demands for flight research.

Second, we review flight research capabilities based on existing NASA flight and ground test assets and examine similar capabilities in DoD, in U.S. industry, and among key foreign partners.

Finally, we compare the needs and capabilities results to identify any gaps or excess and provide a summary of our findings.

Trends in Flight Research Needs

We identified a set of flight research themes and topics based on a review of relevant literature and discussions with flight researchers at NASA and elsewhere. We grouped these potential flight research efforts into three categories. The items listed may be at different levels of abstraction, and are therefore not necessarily mutually exclusive.

1. **Aeronautics system-level efforts** (overarching research that aligns with ARMD's SIP)
   - Environmentally Responsible Aviation (ERA)—advanced transonic designs (SIP: Safe, Efficient Growth in Global Operations; Ultra-Efficient Commercial Vehicles)[1]

[1] See Figure 2.1 for the six SIP thrusts.

- ERA—noise (SIP: Ultra-Efficient Commercial Vehicles)
- ERA—emissions, atmospheric impact (SIP: Ultra-Efficient Commercial Vehicles, Transition to Low-Carbon Propulsion)
- UAS[2]—autonomy (SIP: Real-Time System-Wide Safety Assurance, Assured Autonomy for Aviation Transformation)
- UAS—sensing, perception, and cognition (SIP: Assured Autonomy for Aviation Transformation)
- UAS—communications, networked systems, and cyber/physical security (SIP: Real-Time System-Wide Safety Assurance, Assured Autonomy for Aviation Transformation)
- UAS—human-machine integration (SIP: Assured Autonomy for Aviation Transformation)
- supersonic—low-boom standards and designs (SIP: Innovation in Commercial Supersonic Aircraft)
- supersonic—flight efficiency (SIP: Innovation in Commercial Supersonic Aircraft)

2. **Aeronautics technology areas** (which might drive specific flight research efforts, including with external partners)
   - vertical-lift efficiency and noise
   - high-altitude, long-endurance
   - electric and hybrid energetics
   - drag reduction (e.g., boundary-layer control; laminar flow)
   - engine noise
   - boundary-layer ingestion (BLI)
   - ultra-high bypass ratio (UHBR) engines and propulsive integration
   - advanced composites
   - ultra-efficient airframes
   - Air Traffic Management (ATM)
   - alternative aviation fuels
   - human system integration
   - cockpit information displays
   - sensor technologies and intelligent systems (e.g., flow feature characterization; wake avoidance and system health monitoring)
   - engine and airframe icing
   - hypersonic flight
   - engine emissions

[2] While the scope of this study excluded most UAS as flight research infrastructure capabilities due to them falling below NASA's capital asset threshold (see Chapter One), we did include UAS-related flight research needs because they feature prominently in NASA ARMD's SIP and generally also involve non-UAS capabilities; e.g., manned safety chase planes.

3. **Support to space exploration–related efforts** (from mission directorates other than ARMD)
   – Orion/Commercial Crew flight tests
   – entry, descent, and landing, including hypersonic aspects
   – space planes and air-launched space-access systems.

In terms of resource intensity, the system-level efforts described above are the key drivers and account for a majority of resources. Those efforts relate directly to NASA ARMD's SIP and its six strategic thrusts (Figure 2.1).

Flight Research Needs Derived from the SIP Thrusts

The "Innovation in Commercial Supersonic Aircraft" thrust in the SIP calls for a supersonic low-boom demonstrator. This represents a potentially major investment in test assets and test support platforms. Additional work in the supersonic technology area could involve subscale and subsystem testing in such drag-reduction technologies as supersonic natural laminar flow.

Elements of the ERA program will continue in the "Ultra-Efficient Commercial Vehicles" and "Transition to Low-Carbon Propulsion" thrusts. This research area embodies a broad spectrum of the technology areas, including the N+X airframe program, technology research programs, and projects for both fixed-wing and vertical-takeoff-and-landing vehicles that reduce aircraft emissions and improve flight efficiency. Opportunities for flight demonstrations and research at the transonic regime exist at the subsystem levels. Advanced ultra-efficient airframe concepts (e.g. Blended Wing-Body, double bubble) require flight research with subscale and full-scale demon-

Figure 2.1
NASA ARMD's Strategic Thrusts

SOURCE: Slide reprinted from NASA, 2015c.
RAND *RR1361-2.1*

strators to mature the technology in order for the commercial world to incorporate it in future designs and for government regulators to assess safety.

The "Assured Autonomy for Aviation Transformation" thrust provides the organizing umbrella for forward-looking autonomy and UAS research. Implicit in this thrust is the need to develop flight research capabilities oriented toward human-machine collaboration, system health monitoring, electric and hybrid energetics, software validation and verification, and machine learning and machine cognition systems. Much of this flight research is conducted initially with small and medium UAS to establish proof of concept and mature the underlying technologies. Technologies with the most promise are scaled to larger aircraft (manned or unmanned) and flight tested. In some cases the goal is autonomous medium UAS operating in the National Airspace System (NAS), which requires flight testing in simulated and actual airspace with larger aircraft normally present.

The "Safe, Efficient Growth in Global Operations" and "Real-Time System-Wide Safety Assurance" thrusts in the SIP cover the safety and capacity dimensions of the airspace research program. Airspace-oriented flight research usually occurs to bring the technology readiness level (TRL) to a point where remaining risks are low enough for the FAA or commercial industry to invest in further development and incorporation into their operations. TRL is measured on a scale from 1 to 9, with TRL 1 ("basic principles observed") being the lowest level of readiness and TRL 9 ("actual system flight proven") being the highest.[3] The types of flight tests typically performed for airspace are in an operational environment (TRL 6 and higher). The FAA and commercial partners need a flight qualified TRL 8 to move forward. The flight research objective for airspace technologies is usually to obtain data on a *fleet* of (typically commercial) vehicles in order to capture the impact of external airspace complexity on the technology. The scale of air traffic control–system tests (in terms of the number of aircraft) is so large that NASA frequently has to work with the FAA and engage airlines to support test campaigns. There are occasional tests, typically of subsystems and avionics, that do not require a fleet of aircraft, but they tend to be executed in partnership with industry as well because NASA does not build the avionics needed. Recent examples of collaboration include tools to reroute dynamically around weather (NASA, 2013c) and optimized routing around weather with traffic awareness (NASA, 2015d). The airlines also have a more direct, operational stake in the outcome of the tests and thus stand to more readily capture the externalities stemming from more-efficient flight operations, reduced delays and cancellations, and increased airspace and airport capacity. Historical experience shows that airspace test campaigns place little demand on NASA's own test aircraft fleet.

Beyond NASA, DoD and the commercial aviation industry are major consumers of flight test services. However, the majority of their efforts are geared toward system

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[3] For complete definitions, see NASA, undated.

and vehicle test, evaluation, and certification. The nature of these tests can be very different from the exploratory flight research conducted by NASA ARMD. Still, broad potential exists for NASA-DoD collaboration in hypersonic flight and the development of next-generation fighters (although such collaborations are outside the scope of the current SIP).

In the international arena, Japan and nations within the European Union (EU) have civil aviation research with portfolios similar to those outlined in the NASA SIP. There exists, therefore, the potential for international partnerships and collaborations. The EU Framework Program in Aviation and the "CleanSky" public-private partnership (König and Hellstrom, 2010) bring focus to flight efficiency and emissions in an analogous fashion to NASA's ERA research agenda, with flight research priorities in noise reduction, wake characterization, and natural laminar flow. The Japan Aerospace Exploration Agency (JAXA) also conducts fundamental research and flight research in high-bypass engines, vehicle drag reduction, and noise and emission control under its Environment-Conscious Aircraft Technology Program (ECATP). Additionally, JAXA has a significant flight research–driven program in efficient supersonic flight and sonic-boom characterization/control using subscale UAS gliders dropped from tethered balloons (D-SEND) (JAXA, 2015).

Effect of Modeling and Simulation on Demand for Flight Research

Computational M&S pervades all aspects of contemporary aerospace design, production, test and operations. The M&S tools most relevant to aeronautics research, experimentation and flight research include computational fluid dynamics (CFD), finite element method (FEM), coupled aeroservoelastic simulations, hardware-in-the-loop simulators, airspace and air-traffic simulators and integrated multidisciplinary design, and analysis and optimization (MDAO) environments. The judicious application of validated M&S tools can help reduce design and test uncertainty, increase design knowledge, improve data exploitation, diagnose and understand physical anomalies and reduce cost and risk. At high enough fidelity levels, validated simulations have the potential to reduce the number of test points in a flight research campaign. Sustained improvements in high-fidelity simulation tools may even call into question the necessity of performing tests when comparable simulation capabilities exist. Indeed, an expert panel assessment convened by NASA Langley predicts that "CFD will continue to encroach upon the need for physical testing requirements" (Malik and Bushnell, 2012). This motivates our assessment of the effect of M&S tools on flight research demand, with a focus on CFD, airspace systems, and flight safety simulators.

M&S tools in the three representative categories are mature but have recognized shortfalls in specific capabilities. While further M&S advances may eliminate some of those gaps, the validation and verification of M&S results, as well as the exploration of complex flight regimes and airspace systems still require flight research and demonstration (Tinoco, 2008), as does pushing past TRL 5 (defined as system and component prototype validation in the expected operating environment). When considering the impact of M&S development on flight research, the primary driver is the quantity of work in operational environments (greater than TRL 5).

CFD remains a strong pacing item within the domain of computational simulations. While all simulation tools face analogous challenges and stand to benefit from fundamental improvements in high-performance computing and algorithms, the challenges faced by CFD are particularly acute because of the high mesh density and computational complexity required to resolve complex, viscous flow features. For example, production-grade finite-element analysis is comparatively inexpensive and can be solved at satisfactory grid resolutions for many engineering applications.

While CFD models are quite capable today, they still require significant improvements—as well as extensive validation and verification—to work reliably in challenging flight regimes. In general, CFD can address, with high degrees of confidence, the interior of the flight envelope. For example, the transonic, fully turbulent and attached flow problem (characteristic of commercial transport configuration in cruise) is essentially solved. But flight physics at low-speed, high-lift conditions, as well as those dominated by vortex, transition, and extensive separation and detachment will continue to challenge CFD capabilities in the medium term (Rumsey and Slotnick, 2014; Slotnick et al., 2014). The evaluation and estimation of dynamic maneuvers and stability derivatives are also challenging from the perspective of the sheer quantities of computational resources needed to map out the parameter space. Additional challenges remain in the supersonic (boom characterization, propagation and perception, interactions between shock and boundary layers) and hypersonic regimes (reactive flow). The well-behaved portion of the transonic envelope is important for design optimization of many classes of air vehicles, but makes up only a small subset of tests that are needed to demonstrate airworthiness across the performance envelope. Consequently, flight research will continue to offer critical capabilities in fundamental flight physics research, air vehicle envelope expansion, and final system validation.

Moreover, there is growing consensus that after a period of rapid growth, high-performance computing technologies may have plateaued (Garretson et al., 2005; Malik and Bushnell, 2012, Slotnick et. al, 2014).[4] Moore's law no longer holds when considering current computational paradigms, although unconventional computing technologies such as quantum and biological computing could change the landscape. The path forward using conventional silicon is to combine massive parallelism with heterogeneous, specialized hardware. This may have negative implications for code generality and computation efficiency. On the algorithmic front, the state-of-the-art industrial CFD remains the unsteady RANS (URANS) codes based on algorithms developed through the 1990s. Comparing a technology study from 2005 (Garretson et

4 However, efforts such as the National Strategic Computing Initiative (White House, 2015) are under way to further push technology development in this area.

al., 2005) and 2014 (Slotnick et al., 2014) shows that little has changed in the realm of industrial CFD algorithms and the flow physics that can be adequately resolved.

There are a large number of M&S tools used for benefit assessments of technologies and new procedures in the NAS. The purpose of these models includes measuring and assessing the effects of new technologies, aircraft, and procedures by calculating such things as throughput changes, delay increases or decreases, safety procedures and standards, and reduced fuel burn and emissions. The models include some developed and owned by NASA directly (e.g., ACES, FACET), and others developed by various organizations in academia and industry that have been used in NASA-sponsored studies for related purposes (e.g., LMINET [Long, Eckhause, and Hasan, 2003] and ProbTFM [Gawdiak et al., 2011]). We list the best-known tools here.

- The Airspace Concept Evaluation System (ACES) is a multifidelity M&S system with a full gate-to-gate representation of all major components of the NAS (NASA, 2015h). It has been used to address multiple advanced ATM concept analyses as well as futuristic NAS demands (Young et al., 2011; Eckhause et al., 2013).
- The Future ATM Concepts Evaluation Tool (FACET) is a software tool that provides researchers a simulation environment for preliminary testing of advanced ATM concepts (NASA, 2015i).
- LMINET (from the Logistics Management Institute) and ProbTFM (Probabilistic Traffic Flow Management) have been used to simulate the benefits of large suites of advanced ATM and NextGen concepts with a particular emphasis on NAS-wide benefits.

Just as in the case of platform-level flight tests, extensive airspace simulation capabilities cannot yet replace in-flight validation using in-service aircraft and ground control systems. But just as in the case of experimental aircraft testing, high-fidelity airspace simulation can reduce the uncertainties associated with tests and inform experimental setup, both before and during test campaigns. The concurrent and synergistic application of simulation and test could lead to shorter and more-directed test campaigns.

Flight safety M&S revolves around flight simulators. Again, flight simulators are extremely capable today, but they still have certain physical limitations (e.g., motion, lighting). Moreover, faithful representations of vehicle behavior are fundamentally dependent on our ability to accurately characterize aircraft aerodynamics, dynamic response, and control logic across the flight regime, all of which are subject to the same limitations of disciplinary modeling and simulation tools. Consequently, accurate simulations of aircraft behavior in challenging, nonlinear, and separated flight regimes will continue to depend on results obtained through flight tests. Technology maturation on novel platforms ultimately requires flight research, regardless of how good the simulators are.

The relationship between M&S tools and flight research demand is not characterized by a simple zero-sum game; better simulation tools do not necessarily negate the need for flight research. There remains a critical need for flight research to explore fundamentally new and underresearched flow phenomena and technologies and provide data to validate simulation models. In particular, significant flight regime and flight physics gaps in CFD capabilities are expected to persist over the next 15–20 years as the research community grapples with both significant computational (massively parallel heterogeneous computing) and algorithmic (the need for high-order, low dissipative methods) challenges (Slotnick et. al, 2014).

Concurrently, improvements in M&S capabilities and their integration with flight and ground test processes offer the potential to reduce risks and uncertainties, accelerate and focus test campaigns, facilitate the diagnostics of unexpected and anomalous test results, and improve postprocessing and data exploitation. Particularly powerful is the ability to close the simulation-test loop by refining, calibrating, and executing computational models concurrently with flight research campaigns. A more proactive approach to flight research minimizes remedial actions needed on the test vehicles or specimens and helps anticipate and focus test results. The end results are more-efficient and more-informative tests.

Advances in CFD and FEM can also engender more-innovative concepts and make them ready for flight research. And by cost-efficiently supplementing and replacing wind-tunnel tests in the early design stage, M&S tools could accelerate the process of bringing innovative concepts into tests, which in turn may increase test demand, particularly for small, subscale tests. We expect this trend to be aided by improvements in unmanned systems as low-risk test platforms and by rapid prototyping and additive manufacturing as means to reduce tooling and product realization costs for test articles.

Elsewhere, advances in simulation and integrated multidisciplinary design and analysis capabilities are also pushing the limits of what can be conceived, designed, built, and tested. This, too, may have implications for flight research. For example, the most-profound advances in aviation efficiency in the last half-century have come from improvements in propulsion, specifically through the development and refinement of the high bypass turbofan. The basic aircraft configuration, particularly in the commercial aviation world, has remained largely unchanged. Going forward, more of the savings will likely have to come from the integrated development of unconventional air vehicle configurations, advanced materials, and intelligent control systems, enabled in part by simulation-based, multidisciplinary design tools. It can be argued that approaches to flight that are more active, adaptive, and sensor-rich—such as real-time configuration and trajectory optimization, probabilistic systems for control, network reconfiguration and intelligent control—are inherently more complex, with more degrees of freedom (and, potentially, failure paths). Such configurations may well require more extensive and exhaustive *in-situ* testing since the vehicle performance, flight control systems, and the flight condition will be highly coupled.

Effect of Ground-Based Testing Technology on Demand for Flight Research

Flight research also needs to be considered in the context of a broader constellation of test capabilities that include ground-based test facilities, such as wind tunnels, icing facilities, and engine test facilities. While the ultimate goal of a technology development program is full-scale flight testing to prepare for commercial adaptation, the reality is that ground-based research, when applicable, enables better-controlled environments and much greater levels of instrumentation, and is often more cost-effective. Wind-tunnel tests and flight tests form important critical steps for getting "from here to there" with respect to credible application of simulation outcomes to flight safety, final validation, and certification processes.

Historically, wind tunnels were more cost-effective than flight research for collecting basic lift and drag data about an aerodynamic configuration. In addition to a more-controlled environment and better instrumentation, proper exploitation of scaling laws greatly reduced the size and power requirements of required data collection. But wind tunnels also generally lack the size to effectively test flight dynamics or fluid-structure interactions, especially when scaling does not work.

The growth of CFD—and the expectation that CFD will replace wind tunnels—centers around the "cost-effective" role for collecting aerodynamic data. While CFD is unquestionably more cost-effective for basic data collection, there are limits—due to both a lack of adequate numerical models and a level of computational demand that is not cost-effective. Compared with flight research, ground testing still provides controlled environments that can be more heavily instrumented but ground testing no longer benefits from industrial scales of efficiency, given the modern role of CFD. As a result, flight research is more competitive with ground testing than in the past.

Technology trends related to miniaturization and "big data" are likely working in favor of expanding the role of flight research, especially subscale flight research. Subscale flight test models can be instrumented at far greater levels than in the past. Flight-test ranges can also be instrumented with large numbers of lower-cost sensors tied to large computational power to tease out the required information from the massive quantities of data. While ground testing will continue to lose market share to CFD, it is also key to enabling test technologies applicable to subscale flight research. As long as it is cost-effective and the facilities are available in a timely manner, it is hard to imagine concepts or systems—especially full-scale ones—that should not first be implemented and validated in the controlled environment of a wind tunnel or ground test system. In the future, however, those concepts could be more rapidly miniaturized or adapted to a flight research environment where a greater range of flight dynamics or fluid-structure interaction can be studied.

Three Hypothetical Futures for Flight Research

Based on the considerations we have outlined, we generated three potential futures—steady demand, reduced demand, and increased demand for flight research—as tools to help build, exercise, and illustrate the MOs we created. Scenario uncertainty has two primary sources: what aeronautics research is pursued, and how much flight research is required to achieve the objectives of that aeronautics research. The former is based on continued development of the ARMD research agenda, subsequent prioritization, and management decisions by NASA leadership over the next ten years. Despite the emergence of further details from NASA ARMD on their plans, the future naturally will involve further planning and decisions.

How much flight research will be needed depends on the evolution of M&S and ground testing on flight research needs (see the discussion in the preceding subsections) and both the results of research (always uncertain) and the subsequent management decisions in response. Indications are that M&S advances will lead to more-efficient flight research, but not necessarily less research overall. Also, R&D flight research that does not necessarily lead to an operational aircraft can always leverage more flight research to expand flight envelopes, increase confidence in the data trends, or test alternative configurations.

Despite these limitations (and with the usual assumption that predictions of the future will be imperfect), the potential futures help explore how these factors might evolve, identify management challenges, and ultimately serve as a backdrop against which to illustrate how the MOs we later develop could help ARMD regardless of what occurs in the future.

Future 1: Steady Demand

In a steady-demand future, ARMD funding remains relatively flat. Even with the SIP and an increased emphasis on flight research, priorities and decisions among numerous potential research paths are to be determined. Even though immediate plans and decisions continue to be refined, no plan can cover the next ten years in detail. Changes will ensue. Nevertheless, we developed the following steady-state hypothetical future scenario.

Hypothetical Future 1: Consistent with the current SIP execution directions, a greater focus on low-boom supersonic flight research and continuing growth in UAS research will replace the ARMD ERA effort. NASA would either acquire a modifiable-testbed rotorcraft in partnership with the U.S. Army, or establish a long-term partnership (five to ten years) with a rotorcraft industry partner or JAXA. Flight test of key technologies (e.g., alternative fuels, icing, and hybrid electric research) will continue with the goal of raising their TRLs. In this future, the portfolio of UAS research will expand at both the platform and system levels in collaboration with industry partners. Fundamental flight-based research in UAS (autonomy, sense-and-avoid, human factors, and electric and hybrid propulsion) will continue to grow in importance.

Future 2: Reduced Demand

A minimal scenario (say, from reduced funding) should result in increased prioritization within the SIP. Rather than cutting research in every SIP thrust area, we would expect NASA to keep the fundamental research (which is often less costly than larger-scale flight research) alive and healthy in each area, but focus available flight research resources on only the highest-priority areas. The areas that NASA leadership would select are based on pure speculation on our part since individual propensities are involved, extensive recommendations from research program managers and plan details were not available in 2014, and the selection opportunities will change quickly based on feedback on research progress from both fundamental and preliminary flight research results. With these caveats in mind, we postulate the following hypothetical scenario.

Hypothetical Future 2: Under increased funding pressure, NASA might choose to suspend the planned expansion of low-boom supersonic flight research. Supersonic flight research demands greater funding and depends on more-expensive flight assets, particularly NASA's unique, instrumented high-performance supersonic aircraft. Furthermore, the small transport and business jet-class vehicles likely to benefit most directly from such a technology demonstrator face potential questions of environmental compatibility and economic viability. Hence, it may be reasonable to expect that the supersonic thrust has to cope with additional, nontechnical risks.

Of course, one might argue for flight research cuts in different areas (if, for example, supersonic breakthroughs are game-changing and because prior breakthroughs in supersonics are major successes for NASA). Vertical lift may be another candidate area for reduction (as it has been in the past). Still, a suspension of supersonic flight research for a few years would illustrate how management tools such as longer range planning, mothballing, and strategic upgrading of capabilities could work.

Future 3: Increased Demand

Finally, we explore a future where NASA ARMD resources are well above the annual average of the $578 million from FY 2010–2014. ARMD is on this path already with recent congressional plus-ups in the range of $60 million to 100 million, resulting in an annual average of $641 million for FY 2015–2016. Also, the FY 2017 president's budget requests $790 million, with the ARMD budget growing to more than $1.2 billion in FY 2021, including funding from President Obama's 21st Century Clean Transportation Initiative. If supported by Congress and the President elected in 2016, it would double ARMD's resources.

NASA's FY 2017 budget materials project a number of new major flight research efforts, including hybrid-electric propulsion in FY 2018 and FY 2021, a three-year low-boom flight demonstrator effort starting in FY 2020, and three separate multiyear ultra-efficient aircraft in flight starting in FY 2023. A typical test series is 20–30 sorties, which translates to 30–60 flight hours. Given Armstrong Flight Research Center

(AFRC) utilization rates of about 700 flight hours per year from 2009 to 2014, each flight series is equivalent to 5–10 percent of that annual average. A flight research effort can execute one or two flight series per year—usually limited by resource availability, but sometimes by the need to analyze previous data or modify demonstrators. The FY 2017 budget request could thus increase flight research by 5–20 percent over the next five years and by 20–50 percent in FY 2026, if funded and executed.

Given the timeline of the next ten years, even this optimistic future is limited to existing aeronautics concepts, which have been considered by NASA and the aeronautics community but not yet tested or proven. Even more innovative concepts exist and new ones will likely be developed over the next decade. While some of those concepts may be tested in preliminary flight research, they are unlikely to lead to significant programs in that time.

Hypothetical Future 3: The optimistic, growth-focused future corresponds to significantly increased resources for flight research. This future would include full, robust, stable research in all six SIP thrust areas, additional investments in modifiable testbed aircraft, and initiation of major investments in both subscale and full-scale X-plane demonstrators in multiple areas. In addition to building and flying a low-boom flight demonstrator, ARMD could expand flight research of hybrid electric propulsion concepts on modified testbed aircraft and establish a series of ultra-efficient subsonic flight demonstrators to technically mature a number of mid- to far-future concepts such as hybrid wing body, double bubble, and truss-braced wings. Accelerated flight research of aeronautics subsystems to support the development of those flight demonstrators could include UHBR engines and related propulsion airframe integration of overwing nacelles and BLI.

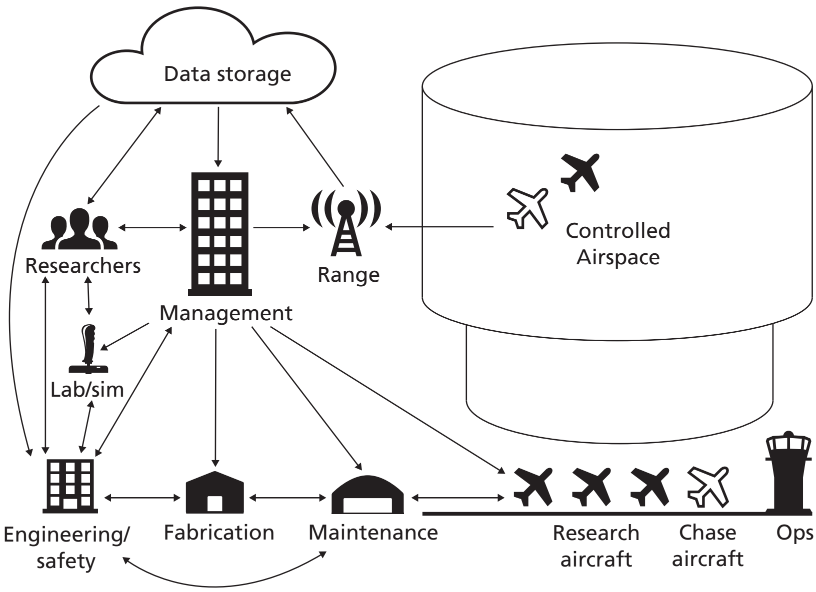
This future also could include ARMD support of increased flight research efforts beyond ARMD into the hypersonic regime, either air-breathing scramjet engine testing or space plane and hybrid space-access systems. DoD efforts toward future high-speed platforms and hypersonic flight, as well as technology development for sixth-generation fighters, also might create demand on NASA flight research capabilities under this future.

Flight Research Capabilities Available to ARMD

Planning how to meet future flight research needs requires a review of the flight research capabilities available. Here, we generally summarize what flight research requires, then discuss the capabilities present within NASA, followed by a discussion of some examples of capabilities available in different potential partner organizations within the United States (e.g., DoD, industry, and academia) and relevant foreign countries.

Flight research requires not only research aircraft but also a range of supporting capabilities as illustrated in Figure 2.2 and described here:

Figure 2.2
Elements of a Flight Research Architecture



RAND *RR1361-2.2*

- research aircraft—the vehicle(s) that instantiate the aeronautic component for study and testing
- chase aircraft that allow for safety checks for aircraft or experiments, airspeed calibration, area chase, assistance with radio calls, escort for distressed return to base, assistance with the performance of emergency procedures or maneuvers, and video or photographic capture for evaluation of test success
- controlled airspace reserved for flight research, which allows pilots to focus on following the research flight plan
- an aeronautical test range providing data telemetry capabilities for real-time tracking and evaluation of test flights, which enables real-time analysis of flight test data and decisionmaking on envelope expansion and other efforts during a flight
- ground-based flight simulation and flight research laboratories to enable risk reduction prior to test flights
- maintenance and fabrication facilities
- data storage and dissemination infrastructure
- a capable workforce and associated management and safety processes, and the regulatory environment in which they exist.

Furthermore, different categories of test aircraft need to be considered:

- X-Planes (either full- or subscale). Aircraft that are custom designed and built to provide demonstration and validation of integrated flight research concepts, where often "the airplane is the experiment" and—in case of full-scale X-planes—cost and risk are generally the highest.

- Modifiable Testbed Aircraft, including:
  - aircraft with modifications to the airframe, where the experiment is integrated into the structure of the aircraft in order to validate components or concepts, with associated increased risk and cost
  - aircraft with a modifiable, digital flight control system (in addition to a certified control system), which allows digital control research and risk reduction
  - aircraft used as flight test fixtures for flight research experiments that can be mounted to the existing airframe, together with additional instrumentation for determining aircraft state or for experiment data collection if required; such aircraft can also be used as support aircraft (safety/photo chase) if needed.

In addition, the capabilities needed for flight research can be very different from those required for flight test. This is because of differences in the level of risk, predictability, and goals of the research. *Flight research* seeks to explore the design space and push the envelope of the state of the art. Thus, it is high risk and not very predictable. *Flight test* activities focus on validating aircraft performance in relevant flight environments. Thus, the technologies and procedures being tested are better developed and thus inherently less risky and more predictable. Although some capabilities may serve both types of work (flight research and flight test), some may be uniquely useful to one or the other, or there may be heavy modifications required in order to make a flight test capability useful for flight research.

The key research question in this context is: What existing and planned flight research, flight test, and safety of flight capabilities are available to NASA ARMD that meet the "capital asset" threshold and could fulfill the flight research needs articulated in the first section of this chapter? This includes ARMD-funded capabilities, other NASA capabilities, and capabilities at external organizations. Here, we provide a summary of these capabilities, starting with those at NASA.

NASA's Flight Research Capabilities

NASA's fleet of more than 60 aircraft—including the aircraft used for flight research—is distributed across several NASA centers. NASA research aircraft are used for both aeronautics flight research and airborne science research.[5]

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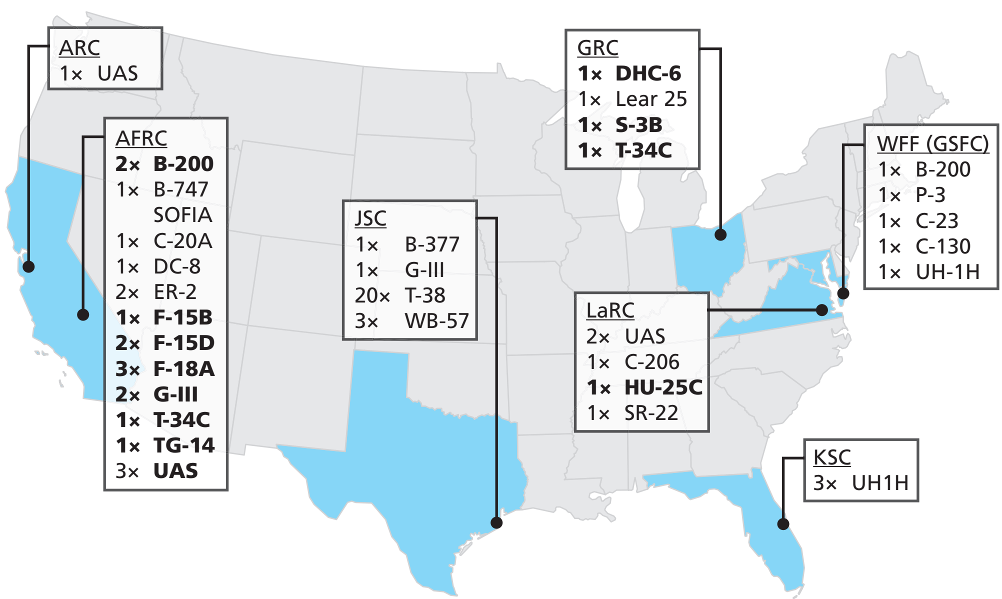
[5] Aeronautics flight research and airborne science differ in terms of both goals and the types of support they need. *Aeronautics flight research* is focused on the science of flight, culminating in aircraft (or other air vehicle) design (NASA, 2014c). Aspects of aeronautics flight research include the study of aerodynamics, propulsion, materials and structures, and stability and control. *Airborne science research* uses airborne capabilities to explore environmental and Earth science research questions (NASA, 2014b). This type of research can include gathering *in situ* atmospheric measurements, collecting various types of imagery, and testing sensor technologies intended for use in space.

Aircraft used for aeronautics flight research are mostly based at AFRC, Langley Research Center (LaRC), Glenn Research Center (GRC), and Ames Research Center (ARC). Figure 2.3 shows types, quantities, and home bases of NASA aircraft, with those of particular relevance to ARMD listed in bold. As the figure illustrates, flight research aircraft are based mainly at three centers, AFRC, GRC, and LaRC, with AFRC hosting the majority of aircraft and related infrastructure. ARC also performs flight research, but mainly with small UAS that were below the threshold included in this study.

Each aircraft type has a given "flight envelope," meaning that due to its design it can fly at certain combinations of speed and altitude. Figure 2.4 shows the flight envelopes for several of the aircraft based at AFRC. In general terms, aircraft that can fly faster and higher are more expensive to operate than aircraft closer to the origin of the flight envelope chart; thus, cost has to be balanced against performance.

Three types of NASA organizations—HQ, centers, and mission directorates—work together to advance R&D through flight research. While all NASA aircraft are owned by NASA as a whole and not by individual centers, centers maintain and operate all aircraft, and keep proficient pilots, maintainers, and other personnel on hand to support missions conducted by these aircraft. Centers have certain areas of focus; for example, AFRC's focus is general flight research, whereas GRC is focused on aero-

Figure 2.3
Locations of NASA Aircraft Meeting the "Capital Asset" Threshold



SOURCE: Based on NASA, 2015a.
NOTE: Aircraft of particular relevance to ARMD are highlighted in bold.
JSC = Johnson Space Center; KSC = Kennedy Space Center; WFF (GSFC) = Wallops Flight Facility (Goddard Space Flight Center).
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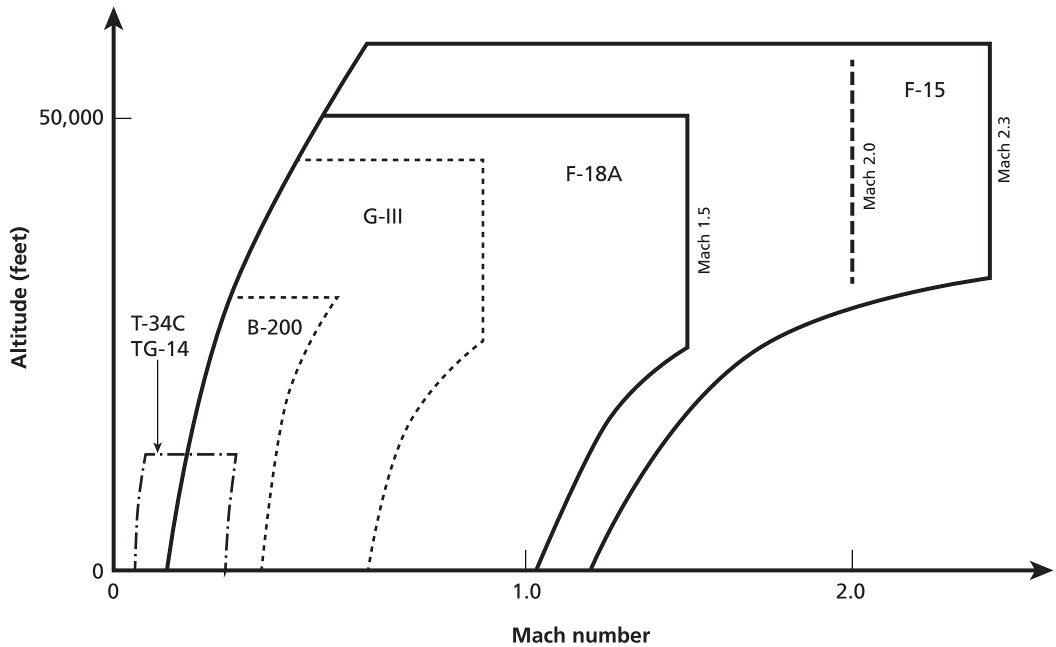
Figure 2.4
Flight Envelopes for Select NASA Aircraft



SOURCE: Reprinted from NASA, 2014g.
RAND *RR1361-2.4*

propulsion and communications technologies (NASA, 2015a). The mission directorates drive R&D portfolios using the resources available at the centers and, along with NASA HQ, make funding decisions and determine investment priorities under the capability leadership of the Office of Strategic Infrastructure's Aircraft Management Division (AMD) and supported by an Aircraft Advisory Committee. Finally, as discussed in more detail in the subsequent chapters of this report, NASA ARMD not only supports individual flight research projects, but also covers the cost of enabling capabilities, like the several airplanes used for chase missions and pilot proficiency training at AFRC, the Dryden Aeronautical Test Range (DATR), and supporting laboratories.

While there is significant cooperation between flight organizations at each center (e.g., through sharing of expertise, cross-checking of safety procedures, and multi-center involvement on specific research projects and technical challenges), the centers remain independent management entities and tend to compete (at least initially) for research work because of the incentive to increase utilization of their capabilities. However, ARMD leadership is already implementing efforts to foster cross-center collaboration for aeronautics research.

A minimum staff size for a flight operation has not been specifically articulated, but required types of personnel include the following (NASA, 2015a):

- Chief of Flight Operations
- Aviation Safety Officer
- Chief of Maintenance
- Chief of Engineering[6]
- Chief of Quality Assurance.

In addition, each flight research effort will require one or more associated researchers and technicians.

Other Domestic Flight Research Capabilities

Additional U.S. Government Flight Research Capabilities

The U.S. Air Force (USAF) has significant capabilities as well (especially at Edwards Air Force Base [AFB]) but focuses on T&E rather than on R&D (412th Range Squadron, 2009). However, the USAF Test Pilot School has some aircraft that can fly research payloads as part of its curriculum. Air Force Materiel Command has established seven Centers of Expertise for T&E consulting, which include the areas of aerodynamic deceleration, arresting gear compatibility, flight training simulation, aircraft integral avionics, flight worthiness, aircraft/cruise missile, and crossover/atmospheric vehicles (aeronautical aspects). Flight test range assets include the Ridley Mission Control Center and Birk Flight Test Facility, supersonic flight corridors, reconnaissance test ranges, defensive test ranges, sea test ranges, offensive weapons test ranges, instrumented armament delivery ranges, terrain following radar range, spin areas, groundspeed calibration courses, Federation Aeronautics International sanctioned speed courses, data transmission and networking, and drop zones.

With AFRC located adjacent to the Air Force Flight Test Center (AFFTC) at Edwards AFB, a longstanding and symbiotic working relationship exists between those two organizations, and the ability for mutual support in a variety of areas—from base operations to specialized maintenance to providing aircraft and pilots for chase missions—is seen as a significant asset by both. However, AFFTC utilization is high and expected to increase further over the next several years, so there will likely be limited opportunities for NASA to "outsource" flight research to AFFTC. In addition, there may be limitations on which USAF equipment may be used, on what timeline, and under what constraints. There also is no national-level, explicit distribution of labor or explicit reliance agreements at the institutional level between NASA and the USAF regarding such topics as which speed regimes each organization will focus on.

The FAA has recently selected six test sites for UAS flight research. The FAA's intent for these sites is to provide a safe environment in which to test UAS in order to advance the " . . . research goals of System Safety & Data Gathering, Aircraft Certification, Command & Control Link Issues, Control Station Layout & Certification,

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6 If aircraft modifications are routinely required.

Ground & Airborne Sense & Avoid, and Environmental Impacts" (FAA, 2015). These sites are operated by the following organizations:

- University of Alaska (approved for operations in May 2014, also includes test ranges in Hawaii, Oregon, Kansas, and Tennessee)
- State of Nevada (approved for operations in June 2014)
- Griffiss International Airport in New York (approved for operations in August 2014, also includes test ranges in Massachusetts and Michigan)
- North Dakota Department of Commerce (two Broad Area COAs [certificates of authorization] were approved for this test site in February 2015)
- Texas A&M University–Corpus Christi (approved for operations in June 2014)
- Virginia Polytechnic Institute and State University (approved for operations in August 2014, includes test ranges in New Jersey and Maryland).

These test sites will be managed by the operators in a manner that facilitates access to those interested in using them. The FAA is responsible both for ensuring that operators provide a safe testing environment and for overseeing that test site operation occurs under strict safety standards.

Flight Research Capabilities of U.S. Industry and Academia

Industry and academia focus on T&E and R&D, respectively. Both sectors offer subsonic research aircraft and the associated workforce (pilots, engineers, maintenance), and often have access to low-density airspace. Some also have ground-based capabilities such as wind tunnels, simulators, or FAA-certified inspectors. Within limits, many claim that they can support new research projects quickly. However, only NASA and DoD currently have supersonic aircraft available.[7]

On the industry side, it is important to differentiate between dedicated flight research capability providers (e.g., Calspan), and aeronautics companies that have their own flight research/T&E capabilities (e.g., Boeing Technology Services—Flight Test, Bombardier Flight Test Center); the latter expect full utilization for years to come and thus may not be able to provide capabilities to outside organizations such as NASA beyond occasional opportunities, such as the EcoDemonstrator partnership between NASA and Boeing. Industry capabilities include aerodynamics research, evaluation of structures and aero-elastics, instrumentation, avionics and systems, provision of test pilots and flight test engineering, unmanned systems integration, next-generation technology development, and navigation of FAA requirements and approvals. Some organizations in particular have a history of working with NASA (for example, Flight Research Associates is headquartered and operates from Moffett Federal Airfield in California, next to ARC) (Flight Research Associates, undated) and DoD (e.g., at Edwards AFB). Note that there are also several companies that lease aircraft for scien-

[7] As detailed in Appendix A, the F-16 VISTA platform is owned by USAF but operated by Calspan.

tific and other purposes that we did not explicitly consider because they are outside of the scope of this research.

University flight research covers a broad range of capabilities, including experimental flight research, wind tunnel testing, aircraft and spacecraft design, aircraft modifications, applied aerodynamics and aerodynamic modeling, flight data models, UAS design and testing, testing of materials, airborne target recognition testing, and a wide range of other engineering activities. Some examples of university flight research centers include Eagle Flight Research Center at Embry-Riddle University, Morpheus Lab at the University of Maryland, Raspet Flight Research Laboratory at Mississippi State University, Texas A&M Flight Research Laboratory, University of Kansas, University of Tennessee, University of Arizona Flight Research Lab, University of Minnesota, and the planned Notre Dame Turbomachinery Facility.

NASA supports flight research in academia, and some academic researchers use NASA facilities for testing. Although this relationship might extend further to NASA taking advantage of university flight research equipment and pilots, these resources are limited. NASA would still likely need to conduct certain types and stages of research at its own facilities to make use of unique capabilities and help ensure maintenance of safety standards. Yet, some academic facilities have fairly advanced and diverse flight research capabilities, certified pilots, and safety processes overseen by NASA, the FAA, DoD (USAF), or some combination thereof. NASA may find it beneficial to consider ways of strengthening and leveraging these relationships. Academic institutions may be able to provide additional assets to enhance NASA capabilities when needed, especially at lower-speed regimes and with respect to UAS. NASA would have to consider the cost-effectiveness of using assets that it does not own and maintain versus any additional regulatory and safety burden it would incur from leveraging partner capabilities.

International Flight Research Capabilities

Many countries maintain some kind of flight test and research capability. However, not all of these have the potential for successful NASA partnerships due to security considerations, size, level of capability, and other challenges. In addition, a full review of all flight research organizations worldwide would be beyond the scope of this work. Thus, we focused on assessing the capabilities of U.S. allies that have demonstrated the ability to conduct flight tests and research at a level roughly comparable to U.S. capabilities and capacity.

DLR (Deutsches Zentrum für Luft– und Raumfahrt), the German Center for Aerospace, is one of the largest national flight research organizations, with a fleet and associated capabilities roughly comparable to AFRC. The Canadian National Research Council (NRC-Canada) and JAXA have fewer capabilities, and are more similar to LaRC or GRC in fleet sizes. JAXA contracts out most maintenance and modifications work, while NRC-Canada and DLR keep much of it in-house.

All three organizations have some underutilized aircraft that they nevertheless keep for potential future needs, and which would thus be available for joint projects with NASA; some of these aircraft would complement NASA's current range of capabilities (see Table 2.1 and Figure 2.5). As with NASA, utilization of aircraft for airborne science flights is higher than for aeronautics research flights. Capabilities beyond aircraft include the "natural" icing environment present in the Canadian Arctic that NRC-Canada and NASA plan to utilize for icing-related collaborative research (NRC-Canada, 2015).

Of note, some organizations benefit from a regulatory environment much more conducive to long-term planning and investing, since they are able to accumulate funding across multiple fiscal years, have more autonomy in setting their own research agendas, and are not prohibited from "competing" with commercial enterprises.

During our discussions with NRC-Canada, DLR, and JAXA, we found support for continued collaboration with NASA, but also heard that national interests of the respective organizations will always be considered first and may sometimes conflict with those of NASA. Some of our interlocutors also mentioned difficulties in formalizing partnerships and joint efforts due to requirements imposed by the U.S. Department of State and its foreign equivalents, which has resulted in missed opportunities in the past.

Potentially suitable international capabilities are also available in several other nations. The Netherlands Aerospace Center (NLR) has both a multiseat jet and a multiseat propeller plane that are used for research. The United Kingdom (UK) has a BAE-146 that has been modified to perform atmospheric research (Facility for Airborne Atmospheric Measurements, undated). Finally, the French Aerospace Lab, ONERA, has capabilities that have recently led to a research collaboration with NASA GRC (ONERA, 2015).

Summary: Current Flight Research Capabilities

Table 2.1 summarizes the aircraft available for flight research at NASA and at potential partners, arranged by speed regime. In addition to listing each type of aircraft, the unique registration numbers ("tail numbers") for each individual aircraft are provided. Ultimately, though there do not appear to be many untapped capabilities, several organizations outside NASA are operating large subsonic testbeds and rotorcraft that may be of interest to NASA flight researchers.

Estimation of Future Flight Research Capabilities

Long-term capability planning stands to benefit from an estimation of future capabilities. However, as with predicting future needs, there is a high degree of uncertainty that precludes exact forecasts. Nevertheless, we reviewed the list of current capabilities provided in Table 2.1 with the main capability providers to identify those aircraft that are expected to retire in the foreseeable future, whether due to reaching flight-hour limits on their airframes or power plants, increased difficulty in obtaining spare parts or other maintenance issues,[8] or a predicted persistent lack of utilization. We also identified some cases in which new aircraft are expected to become available.

Unsurprisingly, most of the changes we were able to identify will take place over the next five years; those are indicated by the items in red in Table 2.2. Specifically, at AFRC, one of the Global Hawks is scheduled to be replaced by another one, and the fate of the SOFIA 747 will be decided in FY 2018. GRC will replace their Lear 25 with a Lear 35, and LaRC is pursuing the acquisition of another HU-25C. JSC's C-9B is already scheduled for retirement, as is one of their T-38s. On the commercial side, the fate of Boeing's current EcoDemonstrators is uncertain, but the company is likely to maintain a comparable capability for the foreseeable future. Internationally, JAXA is not expecting any changes to their fleet, but DLR expects to field a new fuel cell–powered electric aircraft prototype, HY4, later in 2016 (DLR, 2015). DLR was also reviewing its long-term strategic capability needs for flight research at the time of this writing, but had not published any resulting changes to their fleet.

A few additional changes are predicted to occur over the subsequent five years, as shown by the items in red in Table 2.3. AFRC might retire its TG-14 glider if its main utilization area—support of low-boom research—is no longer a focus ten years out. AFRC's C-20A will likely be retired once it reaches the 20,000 flight-hour mark, likely five to seven years out, and one of the F-15s will likely be retired within the next decade as well. ARC expects to acquire two Viking UAS, but the final decision will depend on program needs.

Analysis of Capability Gaps and Excess

As summarized, we characterized ARMD's flight research needs for the next decade, using ARMD's SIP, available NASA planning data, existing programmatic trends, and trends in research methods and techniques (especially potential progress in M&S). We also characterized potential levels of future needs in three hypothetical futures of steady, reduced, and increased demand. There is significant commonality across flight research in the general types of capabilities needed—for example, flight research almost always involves a research aircraft, a test range or airspace, and supporting workforce.

For our gap analysis, we mapped the six strategic thrusts from the SIP against these general capability areas in a matrix to identify the types of capabilities for each thrust and the general availability of those capabilities at or to NASA. Figure 2.5 and the associated discussion show that NASA has existing workforce, test ranges, airspace, and chase aircraft across all its current strategic thrusts. It also has modifiable testbed aircraft in many domains, especially jet and turboprop subsonic fixed-wing aircraft,

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8 See also the discussion of obsolescence issues in Chapter Four.

Table 2.1
Current Aircraft with Potential Utility for ARMD Flight Research

Maximum Speed	NASA							DoD	Industry Partners (Examples)	International		
	AFRC	ARC	GRC	LaRC	JSC	KSC	WFF			DLR	NRC-Canada	JAXA
Low Subsonic (M<0.3)	B-200 (N7NA, N801NA) Ikhana** (N870NA) TG-14 (N149AF)	Sierra** (N707NA)	DHC-6 (N607NA)	B-200 (N528NA, N529NA) *OV-10 (N524NA)* Cessna C206 (N504NA) Cirrus SR-22 (N501NA) *Columbia 300 (N507NA)*			B-200 (N8NA)	MQ-1** MQ-9** RQ-4*,**	Calspan: SAAB340, Hawker Beechcraft Bonanza	DLR-H2 (D-KDLR) Cessna 208B (D-FDLR) DG 300-17 (D-1633) Discus 2C (D-9833) DR400/ 200R (D-EDVE)	Extra 300L (C-FTZE) Harvard Mk IV (C-FPTP) DHC-6 (C-FPOK)	
Subsonic (0.3<M<0.7)	ER-2* (N806NA, N809NA) Global Hawk*,** (N871NA, N872NA) T-34C (N865NA)		S-3B (N601NA) T-34C (N608NA)	HU-25C (N525NA)	B-377 (N941NA) WB-57* (N926NA, N927NA, N928NA)		C-130 (N439NA) P-3 (N426NA) C-23 (N430NA)	C-12 C-130		Dornier 228 (D-CODE, D-CFFU)	Convair 580 (C-FNRC)	Dornier 228 "MuPAL" (JA8858)
Transonic (0.7<M<1.2)	C-20A (N502NA) DC-8 (N817NA) G-III (N804NA, N808NA) SOFIA (N747NA)		Lear 25* (N616NA)		G-III (N992NA) C-9B* (N932NA) T-38 x20			B-2 B-52 C-5 C-17 KC-135	Boeing: 757, 787, Eco-Demonstrators P&W, GE: 747 engine testbeds Honeywell: 757 engine testbeds Calspan: G-III, Learjet	Airbus A320 (D-ATRA) Falcon 20E (D-CMET) G550 (D-ADLR)	Falcon 20 (C-FIGD) T-33 (C-FSKH)	Cessna 680 "Hisho" (JA680C)

Table 2.1—Continued

Maximum Speed	NASA							DoD	Industry Partners (Examples)	International		
	AFRC	ARC	GRC	LaRC	JSC	KSC	WFF			DLR	NRC-Canada	JAXA
Low Supersonic (1.2<M<2)	F/A-18 (N843NA, N850NA, N846NA)							B-1 F-16/ VISTA F-35				
High Supersonic (2<M<5)	F-15 (N836NA, N897NA, N884NA)							F-22				
Hypersonic												
Rotary Wing						UH-1H (N416NA, N418NA, N419NA)	UH-1H (N535NA)	UH-64	Bell: Bell 505	EC-135 (D-HFHS) BO-105 (D-HDDP)	Bell 412 (C-FPGV) Bell 205 (C-FYZV) Bell 206 (C-FZUQ)	BK-117 C-2 (JA21RH)

* high altitude; ** unmanned; italics=flyable storage.
NOTES: M = Mach; P&W=Pratt and Whitney; SOFIA=Stratospheric Observatory for Infrared Astronomy.
Aircraft tail numbers provided in parentheses. The list of "Industry Partners" in the table shows examples but is not meant to be comprehensive.

Table 2.2
Aircraft with Potential Utility for ARMD Flight Research—Five Years Out

Maximum Speed	NASA							DoD	Industry Partners (Examples)	International		
	AFRC	ARC	GRC	LaRC	JSC	KSC	WFF			DLR	NRC-Canada	JAXA
Low Subsonic (M<0.3)	B-200 (N7NA, N801NA) Ikhana** (N870NA) TG-14 (N149AF)+	Sierra** (N707NA)	DHC-6 (N607NA)	B-200 (N528NA, N529NA) *OV-10 (N524NA)* Cessna C206 (N504NA) Cirrus SR-22 (N501NA) *Columbia 300 (N507NA)*			B-200 (N8NA)	MQ-1** MQ-9** RQ-4*,**	Calspan: SAAB340, Hawker Beechcraft Bonanza	DLR-H2 (D-KDLR) HY4 Cessna 208B (D-FDLR) DG 300-17 (D-1633) Discus 2C (D-9833) DR400/200R (D-EDVE)	Extra 300L (C-FTZE) Harvard Mk IV (C-FPTP) DHC-6 (C-FPOK)	
Subsonic (0.3<M<0.7)	ER-2* (N806NA, N809NA) Global Hawk*,** (N871NA, ~~N872NA,~~ N874NA) T-34C (N865NA)		T-34C (N608NA) S-3B (N601NA)	HU-25C (N525NA, TBD?)	B-377 (N941NA) WB-57* (N926NA, N927NA, N928NA)		C-130 (N439NA) P-3 (N426NA) C-23 (N430NA)	C-12 C-130		Dornier 228 (D-CODE, D-CFFU)	Convair 580 (C-FNRC)	Dornier 228 "MuPAL" (JA8858)
Transonic (0.7<M<1.2)	C-20A (N502NA) DC-8 (N817NA) G-III (N804NA, N808NA) SOFIA (N747NA)?		Lear 35 ~~Lear 25* (N616NA)~~		G-III (N992NA) ~~C-9B* (N932NA)~~ T-38 x19			B-2 B-52 C-5 C-17 KC-135	Boeing: 757, 787 Eco-Demonstrators? P&W, GE: 747 engine testbeds Honeywell: 757 engine testbed Calspan: G-III, Learjet	Airbus A320 (D-ATRA) Falcon 20E (D-CMET) G550 (D-ADLR)	Falcon 20 (C-FIGD) T-33 (C-FSKH)	Cessna 680 "Hisho" (JA680C)

Table 2.2—Continued

Maximum Speed	NASA							DoD	Industry Partners (Examples)	International		
	AFRC	ARC	GRC	LaRC	JSC	KSC	WFF			DLR	NRC-C	JAXA
Low Supersonic (1.2<M<2)	F/A-18 (N843NA, N850NA, N846NA)							B-1 F-16/ VISTA F-35				
High Supersonic (2<M<5)	F-15 (N836NA, N897NA, N884NA)							F-22				
Hypersonic												
Rotary Wing						UH-1H (N416NA, N418NA, N419NA)	UH-1H (N535NA)	UH-64	Bell: Bell 505	EC-135 (D-HFHS) BO-105 (D-HDDP)	Bell 412 (C-FPGV) Bell 205 (C-FYZV) Bell 206 (C-FZUQ)	BK-117 C-2 (JA21RH)

* high altitude; ** unmanned; + will retire soon; ?=greater uncertainty; *italics*=flyable storage; red=change from Table 2.1; ~~strikethrough~~ =deletion from what appeared in Table 2.1.

NOTES: TBD=more information was not available. Aircraft tail numbers provided in parentheses. The list of “Industry Partners” in the table shows examples, but is not meant to be comprehensive.

Table 2.3
Aircraft with Potential Utility for ARMD Flight Research—Ten Years Out

Maximum Speed	NASA							DoD	Industry Partners (Examples)	International		
	AFRC	ARC	GRC	LaRC	JSC	KSC	WFF			DLR	NRC-Canada	JAXA
Low Subsonic (M<0.3)	B-200 (N7NA, N801NA) Ikhana** (N870NA) ~~TG-14 (N149AF)~~	Sierra** (N707NA) Viking** x2	DHC-6 (N607NA)	B-200 (N528NA, N529NA) *OV-10 (N524NA)* Cessna C206 (N504NA) Cirrus SR-22 (N501NA) *Columbia 300 (N507NA)*			B-200 (N8NA)	MQ-1** MQ-9** RQ-4*,**	Calspan: SAAB340, Hawker Beechcraft Bonanza	DLR-H2 (D-KDLR) HY4 Cessna 208B (D-FDLR) DG 300-17 (D-1633) Discus 2C (D-9833) DR400/200R (D-EDVE)	Extra 300L (C-FTZE) Harvard Mk IV (C-FPTP) DHC-6 (C-FPOK)	
Subsonic (0.3<M<0.7)	ER-2* (N806NA, N809NA) Global Hawk*,** (N871NA, N874NA) T-34C (N865NA)		T-34C (N608NA) S-3B (N601NA)	HU-25C (N525NA, TBD?)	B-377 (N941NA) WB-57* (N926NA, N927NA, N928NA)		C-130 (N439NA) P-3 (N426NA) C-23 (N430NA)	C-12 C-130		Dornier 228 (D-CODE, D-CFFU)	Convair 580 (C-FNRC)	Dornier 228 "MuPAL" (JA8858)
Transonic (0.7<M<1.2)	~~C-20A (N502NA)~~ DC-8 (N817NA) G-III (N804NA, N808NA) SOFIA (N747NA)?		Lear 35		G-III (N992NA) T-38 x19			B-2 B-52 C-5 C-17 KC-135	Boeing: 757, 787 Eco-Demonstrators? P&W, GE: 747 engine testbeds Honeywell: 757 engine testbed Calspan: G-III, Learjet	Airbus A320 (D-ATRA) Falcon 20E (D-CMET) G550 (D-ADLR)	Falcon 20 (C-FIGD) T-33 (C-FSKH)	Cessna 680 "Hisho" (JA680C)

Table 2.3—Continued

Maximum Speed	NASA							DoD	Industry Partners (Examples)	International		
	AFRC	ARC	GRC	LaRC	JSC	KSC	WFF			DLR	NRC-C	JAXA
Low Supersonic (1.2<M<2)	F/A-18 (N843NA, N850NA, N846NA)							B-1 F-16/ VISTA F-35				
High Supersonic (2<M<5)	F-15 (~~N836NA?~~, N897NA, N884NA)							F-22				
Hypersonic												
Rotary Wing						UH-1H (N416NA, N418NA, N419NA)	UH-1H (N535NA)	UH-64	Bell: Bell 505	EC-135 (D-HFHS) BO-105 (D-HDDP)	Bell 412 (C-FPGV) Bell 205 (C-FYZV) Bell 206 (C-FZUQ)	BK-117 C-2 (JA21RH)

* high altitude; ** unmanned; + will retire soon; ?=greater uncertainty; *italics*=flyable storage; red=change from Table 2.2; ~~strikethrough~~=deletion from what appeared in Table 2.2.

NOTES: TBD=more information was not available. Aircraft tail numbers provided in parentheses. The list of "Industry Partners" in the table shows examples, but is not meant to be comprehensive.

Figure 2.5
Mapping NASA Aeronautics Strategic Thrusts to Flight Research Capabilities

Strategic Thrust	Research Aircraft			Chase Aircraft	Ranges, Airspace	Workforce	Examples for Potential Partners
	Full-scale custom integrative	Subscale Integrative	Modifiable testbed				
1 Safe, Efficient Growth in Global Operations	N/A (staged rollout in real world)	Fleets of UAS (some modified)	Fleets of UAS (some modified)	Safety/observation subsonic AC (FAA req't in some cases)	Test airspace		FAA
2 Innovation in Commercial Supersonic Aircraft	X-plane	X-plane (e.g., LBFD*)	F-15B or D	Sensored and observation sub/supersonic AC	Instrumented range (overland and oversea)		DoD, BizJet
3 Ultra-efficient Commercial Vehicles *Subsonic transport*	X-plane	X-plane (cf. X-56)	Modifiable transport AC (cf. G-III ACTE)	Sensored and observation subsonic AC	Test airspace		Boeing
Vertical lift	X-plane	X-plane (cf. GL-10)	Modifiable rotorcraft	Sensored and observation subsonic AC	Instrumented test range	Engineers, technicians, researchers, management, pilots, etc.	Rotary Mfg
4 Transition to Low-carbon Propulsion	X-plane	X-plane (e.g., SCEPTOR*)	Modified engine AC, hybrid/revolutionary AC	Sensored subsonic AC	Test airspace		P&W, GE, Int'l
5 Real-Time, System-Wide Safety Assurance	N/A	N/A	Modifiable subsonic AC: transport, BizJet, GA	Sensored and observation subsonic AC	Instrumented test range, test airspace		Boeing, BizJet, GA
	N/A	N/A	Icing tanker, subject AC	Sensored and observation subsonic AC	Instrumented test range, test airspace		Boeing, BizJet, GA
6 Assured Autonomy for Aviation Transformation	X-plane	X-plane	Fleets of UAVs (some modified)	Safety/observation subsonic AC (FAA req't in some cases)	Test airspace		FAA, DoD, GA, Int'l

Legend: Available now   Can acquire or modify during project ramp-up   Cannot acquire in advance   N/A

*Not fully/firmly funded yet.
NOTE: AC=aircraft; ACTE=adaptive conformal trailing edge; cf.=comparable to; GA=General Aviation; GE=General Electric; LBFD=Low-Boom Flight Demonstrator; Mfg=Manufacturing. “Int’l” refers to international partners, such as JAXA and DLR.

RAND *RR1361-2.5*

supersonic aircraft, and UAS. Capability projections for five and ten years out show only minor expected changes and thus do not substantially affect this gap analysis.

Gaps

X-plane gaps. X-planes are new vehicles designed specifically for the research in question and, as such, cannot be acquired in advance of the research project. Thus, they are part of the research study itself and must be planned for and budgeted as such. The increasing capabilities of unmanned and autonomous vehicles will provide additional opportunities to realize subscale (and thus lower-cost) X-planes (NASA, 2016a).

Testbed gaps. There are some gaps in the modifiable testbed aircraft category (marked in orange in Figure 2.5). These gaps include an icing research support tanker, a large-scale subsonic commercial transport testbed, and a rotorcraft testbed. The first two were already identified in the 2011 National Aeronautics RDT&E Infrastructure Plan (Office of Science and Technology Policy [OSTP], 2011). Our gap analysis also found that NASA currently lacks a modifiable rotary-wing aircraft testbed as well.

While these testbed gaps exist relative to NASA's SIP, the fact that the SIP is not fully funded makes it unclear if and when NASA would need these testbeds. Since such vehicles are generally available in the commercial market and could be acquired if and when needed (although configuring or modifying them would take some time), it is difficult to make a strategic argument to invest in acquiring such vehicles in advance of definite funding. It is also difficult to argue for advanced procurement of infrastructure on the basis that a research program cannot afford to acquire the testbed itself, since the acquisition would require funds from somewhere in NASA's budget; if NASA cannot afford to fund the program to acquire the vehicle, then they cannot afford to buy it separately, either.[9] However, many of the flight research aircraft currently in NASA's fleet were obtained "for free" from other government organizations (e.g., USAF) and such opportunities are available only occasionally. Thus, relying on obtaining "free" aircraft would require longer lead times.

Other federal organizations, the commercial sector, or international entities could be partners for ARMD flight research using rotorcraft. One company the research team talked to mentioned some interest in a vertical-lift consortium, but that would also require budgetary stability. Finally, some international flight research organizations such as DLR, JAXA, and NRC-Canada, have rotorcraft and expressed interest in exploring potential joint studies or sharing of their capabilities for NASA research. As discussed in the section on partnerships, the challenge for international research is not one of access or statutory limitations, but of whether national goals can be aligned and intellectual property arrangements can be made. The flight research staff whom we

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[9] At NASA, research topics are selected based on a combination of strategic planning at various levels, congressional funding decisions, and presidential guidance, with adjustments made as research progresses and challenges arise. There is no single body that drives NASA's research.

interviewed said leasing was not deemed viable for filling testbed gaps, because testbeds are usually extensively modified, leaving them unfit for subsequent use by others.

Minor gaps. Finally, during our visits and interviews, various parties identified minor component and asset gaps. However, their cost was deemed too small to affect strategic planning concerns and thus those gaps were outside the scope of this study.

Unplanned gaps outside NASA's strategic plan. Of note, the *National Aeronautics RDT&E Infrastructure Plan* (National Science and Technology Council [NSTC], 2011) also identified an overland hypersonics test range as a gap, but hypersonics research is not in ARMD's SIP and therefore is not a strategic concern. One can also argue that an overland hypersonics test range is not feasible, given it is unlikely that a very long, unpopulated strip of land could be quarantined off for such tests. Hypersonics tests are conducted for long distances (many hundreds of miles) over wide oceanic areas that can be cleared of traffic for tests. While it was out of scope for our study to examine specific hypersonic range options, providing improved instrumentation for over-ocean testing appears a more reasonable option. This would also support ARMD hypersonic research included in the latest presidential budget proposal for FY 2017 and beyond (NASA, 2016a).

No major gaps are evident in the areas of chase aircraft capabilities, test ranges, and airspace. However, NASA centers are facing workforce issues related to aging and a slow replacement process; see the "Workforce Capabilities" section in Chapter Three for an in-depth discussion.

There are many examples of successful flight research partnering between ARMD and outside organizations, and ARMD is planning to further expand partnering. However, partnering can also pose challenges and thus needs careful relationship management; see the discussion in Chapter Four.

Excess

We found no current, strategic excess flight research capabilities that do not map to one or more SIP thrusts.

Summary of Findings

ARMD has substantial infrastructure supporting flight research in funded areas. While there are some capability gaps relative to ARMD's SIP, the largest gaps are for X-plane demonstrators whose designs are highly dependent on research program specifics and thus cannot be acquired before those technical challenges are well defined and have high priority in funding. Likewise, there are some gaps in existing modifiable testbed aircraft, but since these are based on modification of commercially available aircraft, their acquisition should likewise await stable, prioritized research plans. We found no strategic excess flight research capabilities that do not map to one or more SIP thrusts.

CHAPTER THREE

Additional Factors Affecting ARMD Flight Research

Flight research at NASA is affected by factors beyond demand and capabilities. Thus, to generate realistic MOs for ARMD to consider, we assessed the ways that the resource environment in which ARMD is situated can affect its flight research agenda. This includes budgets, flight test infrastructure, workforce capabilities, and related issues. This chapter highlights the key insights from those areas.

ARMD Budgets

Budget levels are obviously a key factor for any government activity. NASA ARMD's annual budget has been running at about half a billion dollars since the beginning of the decade.[1] However, Congress has added one-year funding increases ("plus-ups") in the range of $60 million to $100 million in the last few years, and the current presidential budget request shows a significant increase in NASA's budget overall, as well as in the ARMD budget—$790 million for FY 2017 (NASA, 2016a).[2] These recent increases, which together with ARMD's desire to increase flight research led us to emphasize the "increased demand" future for our needs analysis in Chapter Two, support the kind of flight research endeavors envisioned by the authors and the National Academies:

- moderate subscale X-plane projects ($50 million order of magnitude each, spread over three years)[3]

1 The average ARMD budget from FY 2010 to FY 2015 is $578 million (in constant FY 2015 dollars) based on actual NASA ARMD budgets for FYs 2010–2014; enacted ARMD budget for FY 2015 and gross domestic product deflators from OMB (OMB, 1992, Table 10.1).

2 While the current presidential budget request shows even higher "notional" budgets for ARMD in FYs 2018–2021, ranging from $846 million to $1.287 billion, these figures will likely be reviewed—and may be revised—by the new administration taking office in 2017, and are thus affected by a higher level of uncertainty.

3 Subscale unmanned demonstrators can serve as exploratory platforms, but they cannot fully replace full-scale flight research. They are usually significantly cheaper and faster to build than full-size platforms, and enable characterization of some—but, due to scaling issues, not all—aerodynamic effects in flight. They also are subject to more-restrictive volume and power constraints, which affects propulsion and instrumentation.

- small subscale X-plane projects ($30 million order of magnitude each, spread over three years)
- small testbed aircraft projects ($10 million order of magnitude each, spread over three years).

For the first two notional examples, we used the U.S. NRC's recommendation that, in order to make "meaningful progress" (as understood by the NRC panel), NASA should initiate three-year research projects on the order of $30 million to $50 million each (NRC, 2012). The third example illustrates the cost of a much smaller component demonstrator on an existing testbed aircraft.

ARMD is already moving in this direction, moving forward on concrete plans—with associated firm funding of approximately $55 million—for a supersonic LBFD. Efforts are also under way to design and build additional subscale X-planes.

While budget increases are beneficial, the larger question of resources led us to develop management approaches for NASA to consider that could not only help increase budget levels even more, but would also improve the efficiency and efficacy of ARMD's flight research results regardless of budget fluctuations. This includes approaches to manage, fund, prioritize, scope and improve infrastructure investments and capabilities more efficiently.

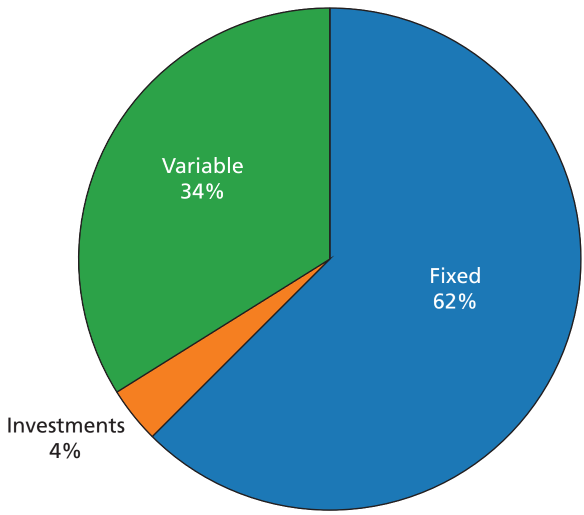
Flight Test Infrastructure

As outlined earlier, NASA owns a large flight test infrastructure to support flight research and testing across the agency. Maintaining and upgrading these capabilities to meet evolving research needs is a nontrivial activity (both managerially and financially). Most of these capabilities take at least a few years to acquire and prepare. Some of these services are unique (especially within the United States), and can only be provided by a few others globally. Many costs are fixed overhead expenses (see Figure 3.1) and must be maintained independent of utilization. These fixed costs mean that less funding is available for acquisition of new capabilities.[4]

ARMD provides some direct support to sustain this infrastructure. A large part of ARMD expenditures for flight research aircraft in recent years has been through ARMD's Aeronautics Test Program, to help cover the cost of supersonic support jets and pilot proficiency planes (mostly NASA's F-18 on the supersonic side and the B-200 and T-34 on the subsonic side). As in the case of the high fixed-cost fraction already discussed, this means fewer funds were available for actual research; however, AFRC

[4] This issue is not unique to ARMD's flight research enterprise. For example, a recent National Science Foundation study on the U.S. Antarctic Program concluded that 90 percent of funds went toward logistics costs and only 10 percent toward the science operations that the logistics efforts are supposed to enable (U.S. Antarctic Program Blue Ribbon Panel, 2012).

Figure 3.1
NASA Aircraft–Related Cost by Type for FY 2013



SOURCE: NASA, 2014f.
RAND *RR1361-3.1*

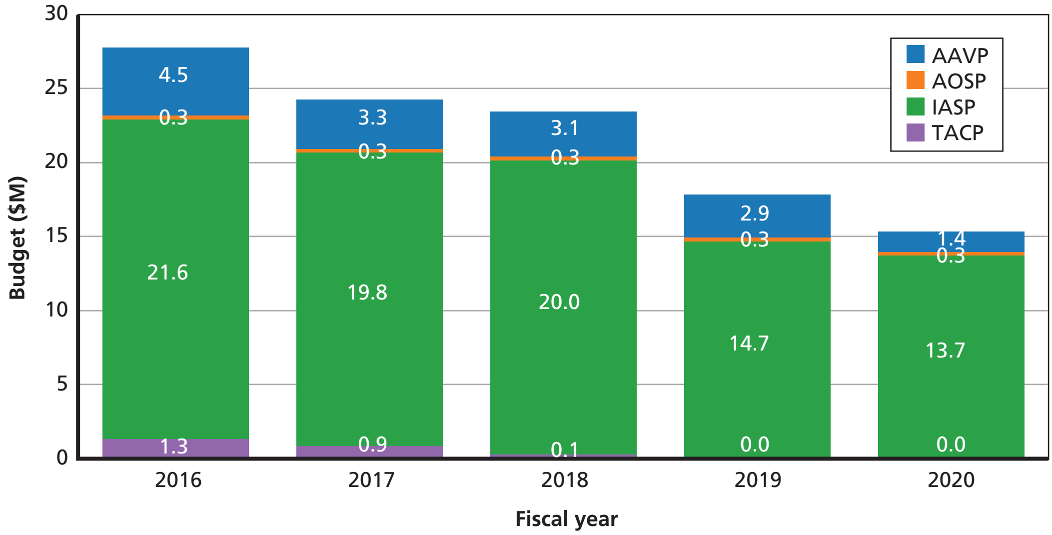
has already been working on converting support aircraft to "dual role" configurations so they can also be used as research aircraft if needed. NASA has been reorganizing how its support is managed, moving it from the old Aeronautics Test Program to be within the research programs that use the capabilities. Figure 3.2 illustrates this support as of the time of this writing. Regardless of how it is paid, NASA's reorganization illustrates that management of this support is an important factor to consider.

Despite a slight downward trend in the number of NASA flight research aircraft over the past several years (see Figure 3.3), reduced flight testing and thus research utilization of some aircraft (especially the relatively expensive high-speed fleet) has been dominated by pilot proficiency flight hours rather than normally scheduled project work for the past several years (see Figure 3.4).[5]

Other capabilities, such as the DATR, have low utilization as well (see Figure 3.5), and capacity reduction efforts are under way (for example, one Mission Control Center at AFRC was mothballed). On the other hand, some of the aircraft used primarily for NASA Science Mission Directorate (SMD) airborne science missions are heavily utilized and are expected to be busy throughout the next several years (e.g., the SOFIA).

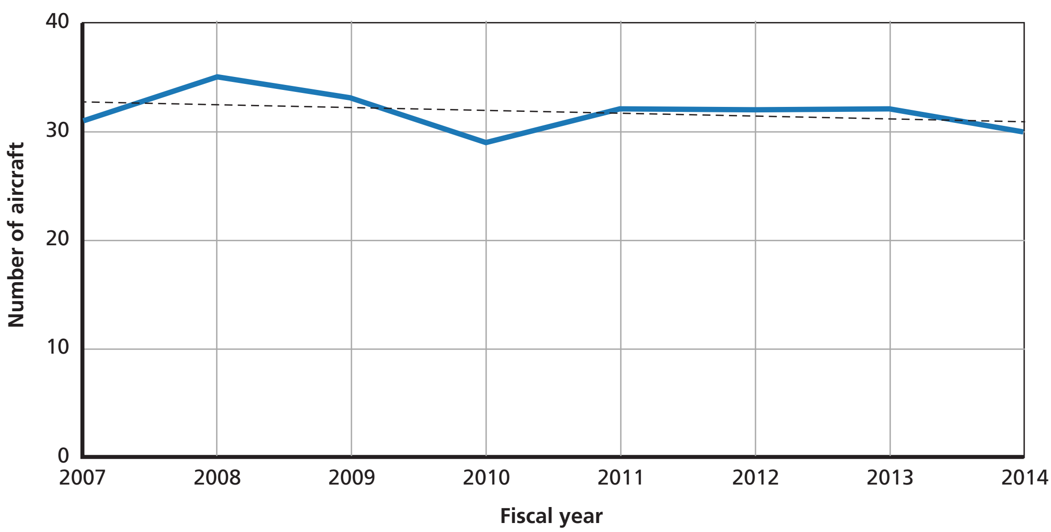
[5] Proficiency training has been identified by AMD as a key operational risk that has to be managed (NASA, 2015a, p. 49), so any reduction in proficiency flights would have to be assessed from a safety perspective as well. Note also that pilots can build some proficiency on regular research flights and that flights in high-performance aircraft contribute more toward test pilot proficiency than those in low-speed aircraft.

Figure 3.2
ARMD Total Aircraft Funding Expected for FYs 2016–2020 (Not Including LBFD)



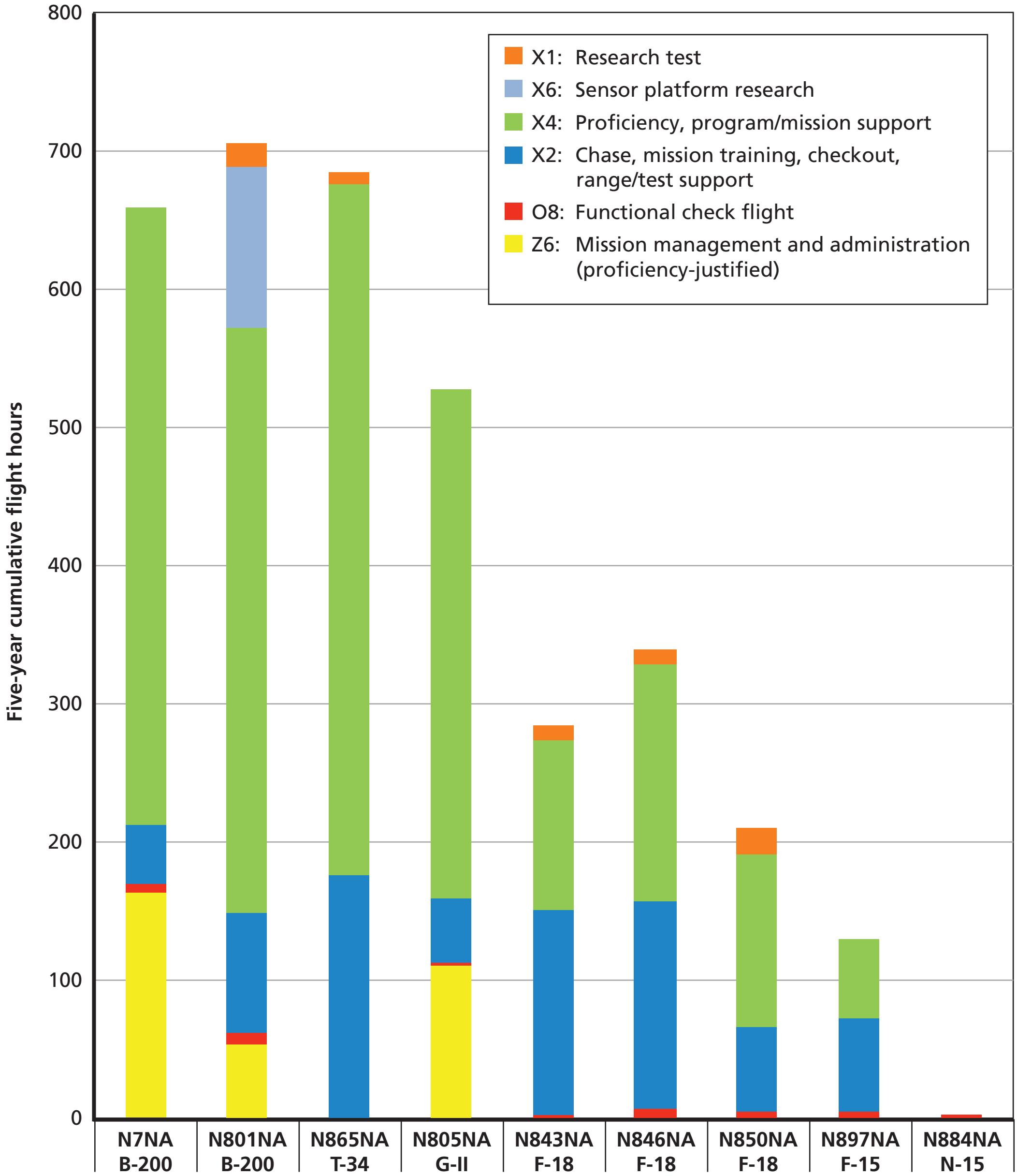
SOURCE: NASA, 2016b.
AAVP=Advanced Air Vehicles Program; AOSP=Airspace Operations and Safety Program; IASP=Integrated Aviation Systems Program; TACP=Transformative Aeronautics Concepts Program.
RAND *RR1361-3.2*

Figure 3.3
Number of Aircraft at ARC, AFRC, GRC, and LaRC (FYs 2007–2014)



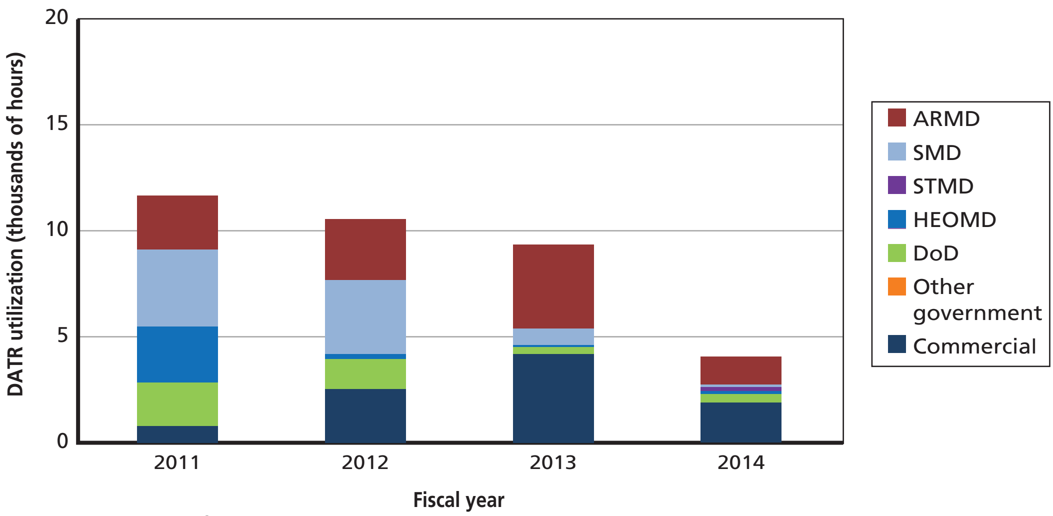
SOURCES: NASA, 2015a, and previous AMD Annual Aircraft Reports.
RAND *RR1361-3.3*

Figure 3.4
AFRC Aircraft Utilization, June 2009–May 2014



SOURCE: Reprinted from NASA, 2014d.
NOTE: N884NA just entered service in 2014 and thus shows very little utilization. Also note that AFRC's main mission for the B-200, G-II/III, and T-34 aircraft is to enable pilot proficiency training for the SOFIA, DC-8, Ikhana, and Global Hawk research aircraft.
RAND *RR1361-3.4*

Figure 3.5
Utilization Trends for the DATR (FYs 2011–2014)



SOURCE: Reprinted from NASA, 2014h.
NOTES: 100% Utilization=15,000 hours. The "other government" category was considered, but did not register in the data.
STMD=Space Technology Mission Directorate; HEOMD=Human Exploration and Operations Mission Directorate.
RAND *RR1361-3.5*

Workforce Capabilities

The flight research workforce is the hardest capability to replace (if, for example, it had to be reestablished after a temporary reduction)—recruiting and maturing skilled flight research staff takes longer than adding instrumentation and other modifications to a new aircraft. The following staff skills and experience are unique to flight research:

- researchers
- airworthiness and flight safety staff (particularly for NASA-unique safety standards and procedures)
- experimental test pilots, who need R&D qualifications (which go beyond T&E qualifications), including for formation flight
- support engineers and technicians.

Maintaining a balanced workforce is challenging not only because of budget concerns but also surges in flight research campaigns. Although gaps might be met using a contracted workforce, there may be issues of skills availability to consider with this option.

For efficient and safe execution of flight research, all of these specialists need to work together closely and contribute to each other's activities and decisionmaking processes. Thus, collocation (or at least the availability of tools and processes for effective remote collaboration) is important, which limits the amount of outsourcing that is advisable and makes geographically distributed operations less efficient.

Based on our discussions with flight research managers at the four NASA centers involved in flight research, the workforce is aging at the same time that employment caps and lags makes hiring replacements difficult, if not impossible. At some centers (but not across NASA), the depth of expertise is already "very thin (one deep)" in some areas relevant to flight research, making it hard to compensate for illness and other unexpected events and to train replacements. As one SME pointed out, staff members involved in flight research also need to have the right mindset: results-oriented rather than procedure-focused. This can be expanded to apply to the "corporate culture" of NASA and its centers. In this context, the workforce management challenges mentioned also make it more difficult to implement organizational and cultural change through changes in workforce.

Finally, breakthrough efforts and successes also attract more highly skilled staff, leading to more breakthroughs—a virtuous cycle, but one that can turn vicious in the absence of breakthroughs.

Some Findings from a Recent National Academies Study Still Apply

It is helpful to highlight findings from the recent National Academies study on "Recapturing NASA's Aeronautics Flight-Research Capabilities":

- NASA does not maintain "strong leadership capabilities in hypersonic flight research and technology" (NRC, 2012, p. 37)—a situation illustrated by the SIP's focus on subsonic and low-supersonic flight; however, the latest presidential budget proposal shows a "Hypersonics Technology Project" as part of ARMD's Advanced Air Vehicles Program (OMB, 2016).
- "A more customer-centric attitude toward the operation of flight research assets could help in establishing new customers for their use, whether in NASA, other U.S. government agencies, industry, universities, or international agencies." (NASA, 2012, p. 50). This ties directly into one of the MOs (MO-13) outlined in the next chapter.

Summary of Findings

Resource limitations and the need to strategically support flight test capabilities are significant challenges for NASA. Ultimately, the most unique flight research capabilities reside with the workforces that maintain, fly, engineer, and provide safety of flight research.

CHAPTER FOUR

Management Options

In this chapter, we present potential MOs for NASA leadership to consider as they strive to increase flight research. Some of the options offered in this chapter address specific challenges identified during the course of the gap analysis and challenge assessments. Other options are aimed at ARMD's intent of increasing flight research in general, including ways to make research dollars go further and increase their efficacy through improved dissemination and access to capabilities and results. As one SME pointed out, while increasing flight research should not be considered an objective in and of itself, more flight research is needed to raise the TRL of more aeronautics technologies to where they can be incorporated into commercial products (for examples, see Klamper, 2009; Warwick, 2015; NASA, 2015c; NRC, 2012). Related options are thus included, as they may help ARMD achieve its strategic objective of strengthening the contributions of aeronautics research to U.S. competitiveness.

Here, we identify and discuss 15 promising MOs. We also briefly discuss additional options that we deemed less viable. In the next chapter, we provide assessments of these MOs to inform our recommendations. It should be noted that NASA already implements some of these options (at least in part) independently of this research, and it should also be noted that implementing several of these MOs would affect NASA entities outside ARMD, which would thus require additional coordination.

Approach Framework

In our attempt to review as broad a set of MOs as possible, after reviewing the needs, capabilities, and other related issues outlined in the preceding chapters, we first listed the range of approaches that NASA might take to increase flight research, across the following space of options:

1. increasing ARMD's overall budget
2. increasing the portion of the ARMD budget that is spent on flight research
3. making the ARMD budget for flight research go further by:
   - improving the efficiency of NASA's flight research enterprise

- taking different approaches to adjust flight research infrastructure
- increasing cost-sharing

4. lowering barriers to flight research
5. better aligning flight research capabilities with research needs.

The first three categories address supply-side improvements, enabling more flight research through increased funding and/or increased efficiencies. The last two categories cover the demand side, making flight research more attractive to researchers.

Based on this analysis along with the research team's experience working on related issues across a range of government organizations, we identified and assessed 20 MOs within this option space. Prioritization led to 15 promising MOs that address the five following areas (see Table 4.1):

- I: Improve Strategic Planning
- II: Partnering
- III: Refine the Scope of ARMD Research
- IV: Identify and Implement Efficiency Improvements
- V: Advocate for Additional Funding

While some of these options are rather obvious and some are already being pursued by ARMD, it is useful to review the entire space of options when conducting such strategic reviews. We also found that these options should be beneficial regardless of whether ARMD's future budgets increase, stay the same, or decrease.

Table 4.1
Top Management Options Identified

Category	Management Option	
I: Improve Strategic Planning	MO-01	Planning integration
	MO-02[a]	Strategic investment
	MO-03[a]	Acquire-at-need
	MO-04	Increase budget certainty
II: Partnering	MO-05	Increase cooperation
	MO-06[a]	Increase partnering
III: Refine Research Scope	MO-07	Space/military tie-in
	MO-08[a]	Annual needs survey
IV: Identify and Implement Efficiency Improvements	MO-09	Cross-center management
	MO-10	Balance risks
	MO-11[a]	Adjust number of chase planes
	MO-12	Voucher system
	MO-13	Streamline process
	MO-14	Improve data access
V: Advocate for Additional Funding	MO-15	Return-on-investment (ROI) analysis

[a] These MOs involve NASA organizations beyond ARMD.

Discussion of Management Options

For each MO, the following aspects are covered:

- motivation for the MO
- who would approve and direct the implementation of the MO
- who would implement the MO
- implementation steps
- rough level of effort
- in-depth discussion
- potential positive effects
- potential negative effects
- effects on other stakeholders.

The information provided for each MO serves to illuminate the details and the pros and cons of each option, but is not meant to be exhaustive. Rather, it is designed to help the sponsor select preferred MOs for further consideration and detailed analysis prior to final decisions regarding which ones to implement and how.

I: Improving Strategic Planning

Several courses of action are available that would improve the alignment between strategic planning for flight research and general research planning.

MO-01: Encourage Integration of Flight Research into Project Plans for Appropriate Research Areas

Motivation: Identifying flight research opportunities in ARMD research projects will benefit ARMD's strategic objective of increasing flight research.

Who would approve and direct the implementation of the MO? The associate administrator for aeronautics would be responsible for this.

Who would implement the MO? ARMD program and project managers would handle implementation.

Implementation steps: ARMD leadership would direct project and program managers to discuss specific plans and schedules for flight research in their plans, including any flight research infrastructure needs, so that infrastructure managers can plan accordingly. If projects will not involve flight research, then plans should make explicit at what future stage flight research is expected to play a role.

Rough level of effort: Modest. Additional planning would be required for many projects; actual level of effort would depend on the level of detail required by ARMD.

Discussion: A direct way to increase flight research (and its benefits) is to encourage aeronautics research projects to examine flight research in their planning and include flight research when appropriate—i.e., when it promises to advance knowledge—in either or both of short- and long-range stages of each project. Of course, not all research projects will benefit from flight research, but if flight research is not appropriate to incorporate into a specific project, researchers should at least create a technology transfer road map showing at what point flight research would play a role in advancing the technology in question toward higher TRLs (and, ultimately, toward transfer to industry).

For example, in NASA's 2015 "Technology Roadmaps", the aeronautics roadmap (NASA, 2015g, TA15) lists 40 enabling technology candidates that are aligned with the aeronautics strategic thrusts. Only ten of the project descriptions provided for those technologies contain explicit references to flight research, while 29 technologies have TRL goals of 5 or higher and would thus require flight research for "system/subsystem/component validation in a relevant environment" (NASA, undated).[1]

On the other hand, while flight research is often seen as a final validation of research, with binary outcomes (the new technology either works or it doesn't) and strong expectations of success, it also can advance aeronautics research by providing a venue for experimentation at the early stage of a research effort, with learning (from both success and failure) as the main objective. Thus, encouraging researchers to make use of flight research for projects where it would otherwise not be considered might help them obtain better results.

Such encouragement also can involve rewarding well-executed flight research; for example, through a policy that provides funding to researchers specifically to attend flight research–related conferences in order to discuss their findings, or an annual award for the "best flight research project" of a given fiscal year. Furthermore, addressing the potential for flight research during the planning phase of each project will also help researchers gain a better understanding of flight research and of NASA's related capabilities.

This MO should be accompanied by efforts to increase awareness of flight research among all aeronautics researchers, as well as by measures that make it easier for researchers to do flight research (see MO-04 and MO-12–MO-14). ARMD managers indicated that they are already implementing some elements of this option.

Potential positive effects: The ARMD goal of increasing flight research would be directly supported, should ARMD management mandate (or even just strongly encourage) the integration of flight research into research plans where appropriate. Because part of the cost of flight research is fixed, any expansion will reduce the average cost of flight testing, to a degree that depends on the fixed-cost share. Better integration would also allow for better long-range planning, thus decreasing schedule risk, particularly for efforts with long lead times, such as flight research requiring significant hardware modifications or specialty aircraft (supersonic, rotorcraft). More flight research would also lead to more opportunities for TRL increases and subsequent tech-

[1] TRL is measured on a scale from 1 to 9, with TRL 1 ("basic principles observed") being the lowest level of readiness and TRL 9 ("actual system flight proven") being the highest.

nology transfer, which increases the impact of ARMD research and can lead to more funding (see, for example, MO-15).

Potential negative effects: At a constant budget, increased spending on flight research would reduce available funding in other areas, such as theoretical research, ground test, and M&S. Thus, flight research should only be required for topics for which it makes sense, and ARMD management would have to make sure that implementing this MO does not end up being just a “check the box” exercise.

Effects on other stakeholders: Negligible. This would be internal to the planning and review efforts within ARMD.

MO-02: Prioritize Investments in Strategic Capabilities

Motivation: Improved certainty in longer-range planning creates an opportunity for considering potential mothballing/reconstitution of any infrequently needed capabilities, and for prioritizing investments.

Who would approve and direct the implementation of the MO? Investment, mothballing, and divestiture decisions involve multiple stakeholders, including the Aircraft Advisory Committee, center directors, and the associate administrators for aeronautics and other mission directorates.

Who would implement the MO? Capability managers at NASA centers would handle implementation.

Implementation steps: Conduct integrated, high-level review of the longer-range plans for infrastructure and flight research capabilities at each center, including consideration of modernization, replacement, mothballing/reconstitution, and divestiture. Decisions should be coordinated with DoD and industry. Annual user surveys (MO-08) would provide additional insights.

Rough level of effort: Modest. Prioritization of investments and explicit strategic planning for assets will involve recommendations and decisions by leadership, assuming improved longer-range strategic planning (see, for example, MO-01, MO-04).

Discussion: ARMD’s SIP outlines NASA’s aeronautics research portfolio for the coming decade. Which flight research capabilities will be needed at any one time will depend on a number of factors, including research ideas, antecedent research progress, leadership priorities and selection, plan sequencing and timing, and budgetary levels. At times, only portions of the capability portfolio may be needed. If ARMD’s efforts become focused on particular areas of the SIP in order to increase the likelihood of generating breakthrough results in this area, then the associated flight research capabilities needed only for those areas could also be prioritized for that same period and then mothballed, at which point research funds (including flight research funds) could be focused on another area and associated capabilities. Such cycles of revolving or staggered activity, including associated mothballing and restoration of flight research capabilities, could be synchronized with NASA’s long-term planning, such as the Aeronautics Roadmap (NASA, 2015g, TA15).

Standard industrial engineering methods are available to compare the costs of continuous production with those of stopping and restarting production. The desirability of mothballing and restoring any aircraft will depend on the particulars of the aircraft and the length of time that mothballing will be expected to continue. To provide a basis for mothballing decisions, the cost of different mothballing and upgrade/replacement options would need to be analyzed.[2] Mothballing costs range from maintaining an aircraft in "flyable storage" to full-fledged mothballing, with engines and instrumentation removed. Subsequent restoration from mothball status to flight readiness includes the cost and time required to reactivate the related workforce through (re)hiring and (re)certifying maintenance staff and pilots. Upgrade and replacement options include transitions to more-modern vehicles (e.g., transitioning from F-15B to F-15C/D variants that are expected to become available as DoD transitions to the F-35, or considering the use of T-38 for certain chase aircraft tasks that do not require significant payload or high-supersonic capabilities). These costs would then be compared with the cost of maintaining a capability throughout a period of underutilization for each aircraft. Such cost analysis should also take into account the effects that mothballing an aircraft or acquiring more-modern replacements would have on overall flight research capabilities (e.g., the aircraft would no longer be available for pilot proficiency flights), and on flight research demand (i.e., the opportunity cost of not having the respective capability available on short notice). Sustainment cost should include the labor cost of pilots and dedicated maintainers, and the cost of proficiency flights and associated maintenance requirements. The income that could be realized by selling an aircraft (versus keeping it in storage) should be included in the calculations, as well.[3]

This kind of cost analysis can help determine, for each aircraft type, the duration of underutilization beyond which mothballing will be more cost-effective. However, limited availability of data on relevant costs and uncertainties of project funding beyond one or two years will make it challenging to implement such cost analysis. For example, NASA does not maintain well-organized cost data on items like those listed in the paragraph above. Furthermore, mothballing and restoration is far more likely to be cost-effective if it lasts for several years than if it only lasts for one or two years.

Another contributor to increasing flight research is ensuring that sufficient infrastructure capabilities are available to facilitate progress, since inadequate equipment and

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[2] As suggested above, the magnitude of the costs associated with each of the items mentioned is an empirical matter that must be examined in the specific context of a particular change in aircraft status and of a particular research portfolio and budget. We have no empirical evidence to offer *a priori* judgments on the relative importance of these items. When other organizations, in the government and elsewhere, ask whether to stop a production activity and for how long, they use standard tools of industrial engineering or operations research. Even as they apply standard tools, they know that the answers they will get depend heavily on the potentially uncertain data related to the decision at hand.

[3] According to NASA's AMD, an agreement between NASA and the U.S. government's General Services Administration (GSA) allows the NASA Center "selling" an aircraft or related parts to keep the proceeds as long as they are spent on aviation-related procurements (NASA, 2016b).

facilities can frustrate researchers. Our review of general infrastructure indicates that most areas are covered by some kind of NASA asset, but some general gaps exist (see our prior analysis of capability gaps and excess). Moreover, detailed needs will arise as specific, detailed plans for research projects are developed. This will include both the designs and alternatives for X-planes, as well as needed component upgrades to existing assets. Finally, the challenges of aging aircraft need to be taken into account when implementing this option; this issue has been studied widely for DoD and industry (Keating and Dixon, 2003; Pyles, 2003; Dixon, 2006; Kim, Sheehy, and Lenhardt, 2006).

One specific category of aircraft that might be subject to cyclic needs is the supersonic fleet. ARMD's SIP is dominated by subsonic research. After the current round of test flights in support of supersonic boom mitigation research and the LBFD, there may be a period of reduced need in which—depending on the expected duration of any gap in supersonic research funding and the need for supersonic aircraft for transonic activities—prioritization on sustainment of subsonic flight research might make sense, especially if workforce capacity (being a major cost driver) can be adjusted as well.[4] On the other hand, if ARMD or other mission directorates consider the continuous availability of supersonic flight research capabilities during such a period to be important in the long run, ongoing strategic sustainment funding would ensure retention of these capabilities. During such a period, longer-term strategic evaluation might conclude that mothballing or upgrading to newer supersonic vehicles is worth the investment, especially given the lull in need.

Potential positive effects: Reducing active aircraft inventory directly decreases cost of ownership, which allows for increased investment in infrastructure improvements.

Potential negative effects: Reducing active aircraft inventory also reduces research and test flight agility, as deprioritized capabilities are unavailable in the short term. It introduces future risk if the required deprioritized capabilities are not reestablished in advance of program need. Reacquisition of divested capabilities would come at an added cost, which—especially for short discontinuities—might exceed the cost saved through divestment, thus emphasizing the importance of thorough cost analysis. Investments in infrastructure without firm identification of needs and prioritized funding (see MO-04) risks wasting resources on infrastructure that will not be used or will be used on lower-priority research.

Effects on other stakeholders: Given that NASA's flight research infrastructure serves external users (e.g., especially DoD and industry), gaps in availability during upgrades and investing, mothballing, and divestiture could affect external users.

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[4] The workforce that maintains NASA's flight research aircraft has very specific knowledge of the unique characteristics of each aircraft that is not formally documented in a complete, systematic way. It could be costly and challenging to preserve and restore this latent knowledge that workers currently carry in their heads if they shifted their attention from current aircraft to others or, even worse, if they left NASA without transferring that latent knowledge to others who stay.

MO-03: Acquire at Need Instead of Sustaining Assets When No Utilization Is Planned for Long Periods

Motivation: Some types of flight research infrastructure assets (especially aircraft) are available on the market. If such assets are not needed in the short term, in some cases it may be more cost-effective to reacquire them rather than sustaining them.

Who would approve and direct the implementation of the MO? Investment and divestiture decisions involve multiple stakeholders, including the Aircraft Advisory Committee, center directors, and the associate administrators for aeronautics and other mission directorates.

Who would implement the MO? Capability managers at NASA centers would handle implementation.

Implementation steps: Identify capabilities that either have infrequent utilization or are current gaps with low-priority or distant utilization plans. Next, assess the availability of such capabilities (as acquisitions from the marketplace or from reliable partners) along with associated costs and lead times. Analyze economic tradeoffs (e.g., using net-present value, as directed by OMB Circular A-94 [1992]).

Rough level of effort: Moderate. Once longer-range planning and prioritization has been accomplished (MO-01, MO-04), then gap and market analysis can be focused on potential opportunities.

Discussion: As discussed in the previous section, when utilization is projected to be low for long periods of time, sustainment costs are likely to be higher than the cost of mothballing (or divesting) followed by reactivation (or acquisition and subsequent modification) once a new need arises.

Many types of aircraft useful for flight research are available on the open market, or are expected to become available in coming years via intragovernmental transfer (e.g., excess F-15 high-performance aircraft from the DoD, once the F-35A is fielded in quantity) or from inside NASA (e.g., excess T-38 astronaut trainer aircraft from the HEOMD).

Management would have to trade budget risk with schedule risk for any decision on acquiring a capability, based on budget certainty—either by acting only when a project that requires a certain capability is fully funded, or by acting early (and thus incurring more risk); for example, when a project and associated need appear in the two-year or five-year budget forecast. However, due to constrained budgets and the high fixed-cost fraction for flight research (Figure 3.1), only limited funding is likely to be available for outright purchases of new research aircraft once the need arises, and obtaining "free" aircraft through intragovernmental transfer requires waiting for aircraft to become available. This can make mothballing a more attractive option because reactivation does not depend on external factors.

When comparing acquisition to retention cost, expenditures for retraining the workforce on a new type of aircraft have to be taken into account as well. This includes maintenance capabilities as well as pilot proficiency. However, an analysis of NASA, USAF, and U.S. Navy data shows that the amount of flight hours needed for a pilot to gain basic proficiency on an aircraft model are comparable to the annual flight hours to maintain proficiency (see Table 4.2).

NASA's recent experience with returning a WB-57 to duty after four decades of long-term storage at Davis-Monthan AFB, requiring a restoration time of approximately two years, illustrates what is possible (NASA, 2015a).

When NASA acquires an aircraft via intragovernmental transfer from DoD, it continues to rely on DoD for parts replenishment and depot-level repair, particularly for avionics and engines. As a practical matter, NASA can keep such an aircraft in its inventory only as long as the DoD supply chain underlying it remains accessible to NASA. That supply chain is likely to be available only as long as DoD continues to use some configuration of the aircraft very close to that of the NASA aircraft. An aircraft with modern avionics and engines, such as the F-15 or F-18, could take significantly longer to return to duty in a configuration consistent with a current DoD version than it took for the WB-57.

This is true whether the aircraft remains in active use or is mothballed for potential resurrection. If a NASA aircraft effectively becomes obsolete while in active use, and NASA still needs the capabilities of the aircraft, NASA must decide whether to modify the aircraft to bring it back into alignment with configurations that remain in active

Table 4.2
NASA, U.S. Air Force, and U.S. Navy Pilot Flight Proficiency: Required Hours

Proficiency Requirement	NASA	U.S. Air Force	U.S. Navy
Flight hours/sorties to *gain* basic proficiency (single aircraft)	NASA prefers to hire proficient pilots. Pilots who are not proficient must undergo training with a proficient pilot.	72.3 hours (F-16)*[a]	80 flight sorties and 67 simulator sorties (F/A-18E)*[b]
Flight hours/sorties per year to *maintain* basic proficiency	150 hours (test pilots) 120 hours (research pilots) 100 hours (other)[c]	108 sorties[a]	120 hours, 6 sorties per month, and fly the aircraft every 10 days[d]
Transferable; reduce hours required for basic proficiency on a new aircraft	Gaining proficiency on one aircraft does not appear to allow for a "fast track" to proficiency on another	Experienced F-15 pilot (500 hours) will be considered experienced in the F-16 after only 100 hours, but this is beyond basic proficiency[a]	Basic proficiency not generally fungible between aircraft. Can get abbreviated CAT-IV syllabus (e.g., between EA-6B and EA-18B)[e]

[a] USAF, 2015.

[b] VFA-106, undated.

[c] NASA, 2011a.

[d] Interview, VFA-106 official, undated.

[e] Interview, U.S. Navy EA-6B pilot, July 24, 2013.

* Does not include mission training. NASA numbers are for test pilots.

NOTES: USAF and U.S. Navy numbers are for combat pilots. An assumption can be made that requirements to remain proficient as a combat pilot are less than for a test pilot; therefore, the Navy and Air Force requirements represent the low end of the scale.

use within DoD, or replace it with another aircraft that has the needed capabilities. If a NASA aircraft effectively becomes obsolete while it is mothballed, NASA need not react immediately. If NASA never needs the aircraft again, it may ultimately not need to do anything. If a need for a mothballed aircraft returns, NASA cannot simply revitalize the aircraft as is; NASA must also bring it back into alignment with aircraft DoD supports, which will add time and financial cost to the revitalization effort. In summary, if a NASA aircraft ultimately becomes obsolete, mothballing it delays the need for NASA to decide whether to bring it back into alignment with current DoD aircraft or replace it.[5]

Potential positive effects: For this MO, any savings depend on the time interval between retirement and reacquisition of a capability that is not needed, since reacquisition involves ramp-up cost (both for hardware and for workforce retraining). Thus, the success of this approach depends on the stability of the strategic plans on which decisions are based, and on the availability of ramp-up funding when needed.[6] Savings for items with low cost of ownership (e.g., UAS that can be stored without incurring much maintenance cost) will be lower.

Potential negative effects: The cost of missed opportunities (i.e., research not attempted because of lacking capabilities) may be higher than the savings and cost avoidance; this is a "chicken and egg" problem. However, this could be mitigated by investing in one or two highly adaptable testbed aircraft that can serve many different purposes. Cost and schedule risk is higher for specialty aircraft (e.g., supersonic, rotorcraft) that are more difficult to acquire and prepare for flight (including workforce retraining/recertification), and lower for near-commodities such as commercial off-the-shelf UAS and subsonic turboprops, business jets, and commercial transport aircraft.

Effects on other stakeholders: As with MO-02, gaps in availability during any divestiture periods could affect external users.

MO-04: Increase Research Project Budget Planning Certainty to Three to Five Years

Motivation: Research and infrastructure managers interviewed said they had high uncertainty on future funding beyond one to two years. The SIP provides the strategic context, but explicit project-level prioritization could improve budgetary certainty and associated planning options for high-priority projects.

Who would approve and direct the implementation of the MO? The associate administrator for aeronautics would be responsible for approval processes.

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5 Longer-range strategic planning as well as budgetary prioritization and stability (MO-01, MO-02, and MO-04) would provide foresight into when specific capabilities are needed. Infrequently needed assets can then be managed relative to their obsolescence and replacement options.

6 ARMD's efforts to expand strategic planning, as well as our recommended MOs to explicitly reduce uncertainty, should help improve the stability of aeronautics strategic plans. Congress is also looking at legislative options for helping to stabilize NASA's budget (U.S. House of Representatives, 2016). Nevertheless, new administrations and congresses have great leeway to revise prior plans.

Who would implement the MO? The associate administrator for aeronautics and ARMD strategic planning staff would handle implementation.

Implementation steps: Organize longer-range project proposals along with rough cost estimates (MO-01) into a decision framework (for example, see Anton, Ecola, et al., 2011) to inform leadership and facilitate ranking based on expected budget levels. The framework can be improved by risk analysis (MO-10). If budget projections only provide a "best estimate" for each year, then identify the top 60 percent of projects as "high confidence," the next 20 percent as "likely," and the last 20 percent as "possible."

Rough level of effort: Modest. Once longer-range plans and cost estimates exist, then ranking can be based on the president's budget proposal for future years and leadership insights on congressional support for the presidential budget projections.

Discussion: One of the most valuable actions ARMD leadership can take to improve its strategic planning is to stabilize planning three to five years out for their research managers. This involves two key elements: (1) continuing to lengthen planning horizons (as in the current SIP activities) and (2) prioritizing activities in the plan. Stable plans will help not only research planning but also infrastructure planning and investment. The latter is important to efficiently prepare capabilities given required lead times while avoiding waste from unused capabilities or capacity.

While Congress controls ARMD's yearly budget levels, much of the uncertainty lies at the margins—not in the bulk of the budget—and ARMD has significant latitude in prioritizing research within its budget. Thus, if projects and technical challenges were explicitly prioritized, then ARMD could provide reasonably high confidence to the highest-priority projects and allow their project leaders (and their associated infrastructure providers) to maximize efficiency through anticipated stable plans (modified, of course, based on research progress) and fairly confident funding streams. For example, priority projects funded with the first $400 million per year in ARMD's budget could be designated "highly confident;" those project managers should optimize their plans based on the expectation of stable funding and not waste time in planning contingencies. Projects funded with the next $100 million could be designated as "confident," and managers could prepare in similar fashion. On the other hand, projects whose funds fall below the first $500 million of the ARMD budget (including recent congressional plus-ups of $60 million to 100 million) would be told that their budgets are less certain; thus, they need to plan for contingencies to handle budgetary uncertainties (higher or lower) over the next few years. These priorities, of course, are separate from the normal uncertainty of research progress and associated cuts.

While NASA does not control its budgetary fate and thus seemingly cannot assure budgetary stability, it has historically been granted wide latitude in prioritizing and managing research details within a large budget. Thus, assuming stable or increasing overall funding, this is one of the easiest options to implement since it would only require leadership commitment to—and effective communication of—such prioritization to project managers and researchers. In fact, better communication may be all that is required. While we heard from some sources at ARMD HQ that such planning certainty exists, some center-based researchers were unaware of this and were planning based on year-to-year funding.

Potential positive effects: Implementing this option would allow for more efficient long-term planning and ramp-up, reducing schedule risk and wait times—particularly for flight research with long lead times (e.g., involving significant hardware modifications or complex custom-built test articles). Increased stability in research project budgets could also increase overall flight research, because longer-term funding would be more certain for higher-priority projects and technical challenges, in turn improving utilization and spreading nonrecurring fixed costs across more projects. Finally, once longer-range plans are developed, project managers could focus more on research than on having to worry about budgets on an annual basis.

Potential negative effects: Providing stable funding beyond the annual budget cycle requires explicit leadership efforts to prioritize research activities and also hinges on the stability of NASA ARMD's overall strategic planning (i.e., between changes of presidential administrations). It may also reduce the amount of short-notice funding available for urgent needs.

Effects on other stakeholders: Negligible. This is an internal NASA prioritization. It could, however, help external parties better understand specific implications of NASA's strategic plans and the importance and effects of stability in NASA's aeronautics budget.

II: Partnering

Bringing in funding and/or capabilities from organizations outside NASA can also contribute to increased flight research, reduced cost, and increased efficiencies. Furthermore, fostering collaboration and partnerships is one of NASA's original objectives, declared in Section 102(c)(8) of the National Aeronautics and Space Act that established the Agency (Public Law 85-568, 1958).

MO-05: Increase Cooperative Research

Motivation: NASA has flight research capabilities that could be useful to external organizations. Contributing these assets as part of cooperative research activities on a cost-reimbursable basis can help sustain these assets by sharing operating costs and bringing in additional funding. In-kind contributions may serve NASA's larger mission and support specific research objectives. Cooperating with external researchers will also bring in their know-how and expertise.

Who would approve and direct the implementation of the MO? The strategic context for cooperative research is set by the associate administrator for aeronautics. ARMD project and program managers generally explore individual opportunities. The associate administrator for aeronautics and center directors, as well as NASA's Office of General Counsel, approve the final plans and arrangements.

Who would implement the MO? Project and program managers with center infrastructure managers would handle implementation.

Implementation steps: Specific steps vary by case. Usage costs are generally set using existing price schedules, although in-kind support is approved on a case-by-case basis.

Rough level of effort: Moderate. Level of effort varies widely depending on the equities involved and the level of participation by external parties.

Discussion: This MO involves fostering collaboration and cooperation with outside organizations (other government agencies, industry, academia) that are interested in performing flight research using NASA capabilities, usually on a cost-reimbursable basis.

NASA policy, as understood by interviewees in this study, is to avoid competing with the private sector and only offer facilities and services for work in keeping with NASA's mission. More specifically, NASA employees believe they can only offer NASA facilities and services on a reimbursable basis if the facility or service is not otherwise available commercially. This may include multiple facilities or services that are available commercially but are collocated at NASA in a manner that facilitates the research activity in a unique or noncommercially available fashion.

Current, directly relevant policy documents are silent on the matter, although earlier policy documents were explicit that NASA was not to compete with industry. The 2006 *National Aeronautics R&D Policy* stated that U.S. government R&D "goals must be scrutinized to ensure that the government is not stepping beyond its legitimate purpose by competing with or unfairly subsidizing commercial ventures" (NSTC, 2006). The 2007 NASA Policy Directive on reimbursable use of NASA facilities by foreign entities, which references the 2006 national policy and remains in effect, states explicitly, "NASA shall not compete with the private sector" (NASA, 2007). However, the 2010 *National Aeronautics R&D Plan* (NSTC, 2010), which does not necessarily supersede the 2006 policy, and the NASA policy directives on Space Act agreements (NASA, 2008) and cooperative R&D agreements (CRADAs) (NASA, 2013a; discussed further in MO-06), are silent on competition with industry. The reference to foreign entity research in the policy directive may create some confusion, so NASA leadership should consider making all policy documents consistent. There is also no blanket legal prohibition on NASA providing services that are otherwise available in the private sector.

Increasing the quantity and quality of cooperative efforts requires management attention to several issues:

- an organizational culture and workforce that can provide good customer service, appropriate reward structures, and other motivators
- proper sharing of credit with partners, including through proper planning of any outreach activities and publications, something particularly important in fostering long-term partnerships

- making sure research that is brought in is in general alignment with NASA's mission, while avoiding a "what's in it for NASA" mindset. Table 4.3 shows an example of such an appropriateness assessment, listing all the criteria that a cooperative research or partnering proposal has to meet. This could be revised and adapted with an expansion of collaborative research in mind.

Examples of existing collaborative efforts include AFRC support to USAF for KC-46 testing and to Jet Propulsion Laboratories for Mars Lander Light Detection and Ranging (LIDAR) testing, as well as ARMD collaboration with Air Force Research Laboratory (AFRL) on conformal flap technology (such as ACTE).

Potential positive effects: Focusing on collaboration with organizations interested in using NASA flight research capabilities would bring in external know-how and funding, thus lowering costs for NASA.

Potential negative effects: Inefficient collaboration can add cost and program management risks and difficulties if not managed properly. Increased dependence on outside entities can introduce schedule risk; moreover, setting up collaborative efforts takes time. Also, NASA focus can be diverted from its core agenda if collaboration

Table 4.3
Notional Decision Criteria for Appropriateness of Flight Research Efforts

Criteria	Measure		Typical Implications
Fits National Research Agenda	Traceable to guidance from the National Academies or NASA appropriations text		Not very restrictive ARMD projects should already align
Appropriate for flight	Flight is the best (or only) way to obtain the relevant environment		Research is sensitive to: • Aerodynamic scaling or enthalpies that cannot be simulated in ground test • 6 DOF flight mechanics • Properties of the natural atmosphere • Complexities that cannot be modeled
	AND: Technology is sufficiently mature		• History of lower TRL development • Critical physical parameters identified
	AND: Flight experiment will be effective		• Proven test techniques • Scientific method in experimental design
Appropriate for government	Results will have broad value and be applicable to a class of applications		Findings will not be product-specific No proprietary restrictions, should produce research reports and papers
	AND:	Technical or programmatic risk is too high for industry	Big, expensive projects with little short-term pay-off (X-planes) High technical uncertainty
		OR Unbiased testing is of national benefit	Findings are sensitive to competitive interests: industrial, political, academic
		OR Only required for NASA mission	Development of flight test techniques relevant to NASA research missions

SOURCE: NASA, 2014i.
NOTE: DOF=degrees of freedom.

projects do not meet criteria for appropriateness; however, collaboration interest can also be an indicator for changing community needs (MO-08).

Effects on other stakeholders: Cooperative research can facilitate research and may incur financial reimbursements to NASA as well as the sharing or restriction of research results (per the negotiated agreement).

MO-06: Increase Partnering

Motivation: Using flight research capabilities provided by external stakeholders can create research opportunities and facilitate technology transfer.

Who would approve and direct the implementation of the MO? The strategic context for cooperative research is set by the associate administrator for aeronautics. ARMD project and program managers generally explore individual opportunities. The associate administrator for aeronautics and center directors approve the final plans and arrangements, with the advice of NASA attorneys.

Who would implement the MO? ARMD project/program managers and center infrastructure managers would handle implementation, although strategic partnerships entail significant involvement of NASA leadership.

Implementation steps: Specific steps vary by case. Generally, project and program managers utilize their knowledge of external organizations to identify partnering opportunities. Equities and value propositions are developed and negotiated, including intellectual property rights to any research results.

Rough level of effort: Moderate to high. The level of effort varies widely depending on the equities involved and the level of participation by external parties.

Discussion: NASA has successfully utilized partnerships in the past and plans to continue doing so. Partnerships with outside organizations (other government agencies, industry, academia, and international organizations) that have flight research capabilities of interest continue to be an important option to NASA. Partnerships can extend NASA's research by leveraging external capabilities, reducing the need for NASA ownership of those capabilities, and promoting technology transfer and application of research. Appendix A provides in-depth discussion of specific partnering opportunities with external organizations, and of limitations and practical considerations related to partnering.

ARMD's "Partnership Strategy" and NASA's new "Partnership Council" are efforts already aimed at increasing partnering at the mission-directorate and agency levels, respectively.

Potential positive effects: The positive impacts of increased partnering are dependent upon the type of partner as well as the partnership arrangement. Partnership could allow NASA to divest itself of some of its own capabilities, and to access capabilities that are not currently available inside the organization. In both cases, cost could be reduced. Cost savings related to supersonic research could be particularly high due to the high cost of supersonic capabilities. Time to flight can be reduced if the partner has a needed capability ready to go. The four scenarios explored in Chapter Five offer details specific to partner types and arrangements. Furthermore, long-term strategic support of external capabilities would ensure that those capabilities are maintained and available to NASA researchers.

Potential negative effects: Again, the impacts in this category are contingent upon type of partnership and arrangement. In general, an increased dependence on outside entities needs to be managed carefully to avoid increasing schedule risk, cost risk, program risk, and safety risk. Finding partners and setting up partnerships takes time, especially with foreign entities. However, this is likely less of an issue in areas that have many potential partners (e.g., UAS research). Regarding long-term strategic support of external capabilities, these agreements involve significant time and effort to establish and maintain, including dedication of stable funding.

Effects on other stakeholders: Partnerships, by their very nature, have direct effects on the external parties involved, including cost-sharing, sharing of available assets and intellectual property rights, and introducing interdependencies.

III: Refining the Scope of ARMD Research

Connecting ARMD research to areas that already have a strong support base—and associated funding streams—can help increase flight research as well, as can making sure that flight research capabilities are aligned with the needs of the community.

MO-07: Expand and Highlight Ties to Space Exploration and Military Applications

Motivation: Space exploration and military systems continue to have needs for advancing aeronautics concepts. Related programs can serve as additional sources of funding for ARMD's research program.

Who would approve and direct the implementation of the MO? The associate administrator for aeronautics would be responsible for approval.

Who would implement the MO? ARMD's strategic planning team would explore opportunities with external stakeholders. Specific research projects would be further developed and executed by designated project and program managers.

Implementation steps: Develop a list of aeronautics-related challenges in these domains that would benefit from ARMD assistance. Examples include hypersonics (space and military), exoplanetary re-entry and space planes, next-generation military fighters, the Future Vertical Lift program, and the DoD's current initiatives to pursue technical advantages (third offset strategy, etc.). Reach out to external stakeholders, conducting exploratory meetings on ways in which ARMD can support efforts in these areas.

Rough level of effort: Moderate to high. Establishing ties is likely to involve extensive discussions and negotiations, given that ARMD does not have primary responsibility for these research areas. However, areas such as hypersonics have well-established coordination panels.

Discussion: A different strategic approach for pursuing increased budgets is to tie ARMD flight research to subject areas that already have strong support. For example, NASA is widely viewed by the public as the space agency. There are innovative space-related aeronautic topics that could be emphasized, such as exoplanetary aeronautics (e.g., Mars flyers such as ARES).[7] Another example is military and dual-use military/civilian aeronautics research. NASA has a long history of partnering with the DoD on aeronautics (see, for example, Bilstein, 1989). Although ARMD's SIP focuses exclusively on civil aviation (NASA, 2015c), topics such as the Air Force's renewed interest in hypersonics (USAF, 2014) and DoD's emphasis on innovation (e.g., Office of the Secretary of Defense, 2014) could serve as a catalyst for increased and innovative flight research in the many areas where NASA has a unique value proposition to offer.

Furthermore, mutual support between NASA and the military is one of the objectives specifically mentioned in the Aeronautics and Space Act (Public Law 85-568, 1958, Sec. 102[c][6]). Thus, while the SIP focuses on civil outcomes, this does not preclude cooperation with the military on research of common interest, and there is active collaboration in those areas. Thus, further expanding tie-ins to these areas could increase the value and impact of aeronautics research. However, this would entail a strategic shift in priorities or require further dramatic increases in funding in order to first fully fund the current SIP priorities.

Potential positive effects: Beyond increasing funding for ARMD research, this might also improve collaboration with NASA's space-related mission directorates and DoD. As with MO-05 and MO-06, the fixed costs of maintaining unique flight research capabilities would be spread across a larger user base.

Potential negative effects: Depending on the level of implementation, this could dilute ARMD's current focus on commercial aviation needs, and might lead to conflicts over funding, control, and division of labor with the organizations that have primary responsibility for space and military flight research.

Effects on other stakeholders: ARMD participation could directly support the space and military R&D goals of the federal government.

MO-08: Perform Annual Survey of Requirements, Needs, and Ideas

Motivation: Annual surveys would help improve communications between researchers, ARMD, and infrastructure managers.

Who would approve and direct the implementation of the MO? Center directors and the associate administrator for aeronautics would be responsible for approval.

Who would implement the MO? NASA infrastructure managers would handle implementation (or a centralized, matrixed organization would, in the case of MO-09).

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[7] See, for example, the Aerial Regional-scale Environmental Survey of Mars (ARES) proposal for a "Mars Scout" mission, although it was not funded for implementation (NASA, 2011c).

Implementation steps: Leverage existing commercial, web-based survey products or NASA in-house capabilities to solicit annual feedback from researchers across NASA, industry, and academia on flight research ideas and infrastructure requirements. The quality of survey results often benefits from the advice of survey researchers, especially if they are involved in the initial design of the survey instrument.

Rough level of effort: Modest. Commercial survey products and NASA SMD's survey system are readily available at low costs for collecting and integrating survey data.

Discussion: Capturing the demand signal and related developments across the U.S. flight research community by being more engaged in finding out about user ideas, needs, and priorities would facilitate strategic management of flight research, and could also contribute to increasing the base of potential users. ARMD could institute a formal and well-publicized annual survey, similar to what SMD is already doing (NASA, 2015a, p. 42; NASA 2015f). Such a survey could be complemented by an effort with a longer-term horizon, such as the Decadal Surveys that are regularly provided for several other areas of scientific research (e.g., particle physics or planetary science). Prioritization is key, and survey results will have to be reviewed and prioritized with respect to existing strategic efforts, such as the strategic thrusts in the SIP. This could be done, for example, by a flight research board at ARMD HQ. The only "Decadal Survey for Civil Aeronautics" done so far was less useful in this respect, because it did not sufficiently prioritize among the 51 "highest priority research and technology challenges" it listed.

Potential positive effects: Basing planning more closely on demand can reduce cost to NASA and help refine strategic planning. Validated requirements also reduce schedule risk by informing the acquisition process.

Potential negative effects: There will be some implementation cost, but that will likely be much less than potential savings and avoided cost. However, a formal survey may also create expectations on the part of those surveyed, some of which might conflict with existing strategic planning.

Effects on other stakeholders: Survey participants will have to invest time to complete the survey, ranging from modest to moderate (minutes to days)—the exact amount depends on the breadth and depth of the survey questions.

IV: Identifying and Implementing Efficiency Improvements

Regardless of whether ARMD's budget increases, stays the same, or decreases, improving the efficiency of available dollars is critical. NASA, like many organizations facing persistent budget shortfalls, has already been working on increasing its efficiencies, but we identified several related MOs for consideration. The options also include lowering the barriers to access and thus encouraging researchers to make increased use of flight research capabilities. Note that some of these options cannot be implemented by ARMD alone because they affect NASA center and NASA HQ assets and roles.

MO-09: Institute Cross-Center Matrix Management of Flight Research Capabilities and Partnership Outreach

Motivation: Matrix management has been used successfully for decades in the commercial sector to improve coordination, outreach, and information flow in support of disparate units.

Who would approve and direct the implementation of the MO? NASA leadership (including, at least, center directors, the associate administrator for aeronautics, and the associate administrator for science) would be responsible for approval.

Who would implement the MO? This remains to be determined, but a transition committee with managers from the primary flight research centers (e.g., ARC, AFRC, LaRC, and GRC) and NASA HQ, together with a lead from ARMD, would be a logical option to work out the details.

Implementation steps: First, a strategic concept would have to be developed and approved (notional ideas are discussed later). Next, operational details and associated agreements would have to be prepared for leadership review and ultimate approval.

Rough level of effort: Moderate to high. The biggest part of the effort would be to develop specific organizational options, then develop stakeholder feedback, revisions, and support. Implementing the reorganization is conceptually simple—but, depending on the implementation, details may involve some administrative changes and associated cost.

Discussion: Significant effort and progress have been made to increase cooperation between, and joint participation among, NASA research centers in providing flight research assets (e.g., aircraft and test infrastructure) to aeronautics flight research. Recent research programs have utilized assets from different centers and leveraged expertise across NASA, although different cultures among centers can still lead to disagreements. Also, the flight operations organizations at different centers share knowledge and provide cross-center quality checks (e.g., to examine each other's flight safety procedures).

This progress could be further facilitated by instituting a matrix management that integrates these capabilities while continuing to provide local presence and service at different research centers. Despite the successes mentioned above, the flight research organizations do not belong to the same organization; staff in each local office belong and report to their local center director. This structure sets up a natural tendency for staff to advocate for local capabilities when talking with programs about future research. Some organizations framed this as a friendly competition to provide support to programs.

A new cross-center matrix management of flight research and operations centers could facilitate further cooperation and coordination among these organizations. Matrix management structures are a well-established business practice in the commercial industry that breaks down barriers and local parochialisms while facilitating the ability to serve different line units, make capabilities available more broadly, provide shared surge capabilities, and identify efficiencies. Under such a structure, the flight operations organization at each center would belong and report to a single NASA management organization. They would be matrixed to support local research at the center where they reside as well as needs and projects based at other centers. Designing the best matrix structure for NASA's flight research operations is beyond the scope of this study, but Figure 4.1 illustrates how it might be set up. Staff would work objectively to facilitate access to any NASA flight research capability, regardless of location. Thus, for example, a capability staff member at one NASA center might have a local aircraft that can serve a local researcher's needs to a degree, but the staff member might know of a better asset (and its availability) at another center. Capability staff members would therefore represent all of NASA's capabilities and provide immediate advice on their strengths and shortcomings with respect to a specific researcher's needs, simplifying coordination between assets housed at different centers and working to provide the best resources to researchers—not just local ones. Thus, they would serve as a one-stop-shop to facilitate knowledge and access to all NASA capabilities, introducing added value to the local researcher.

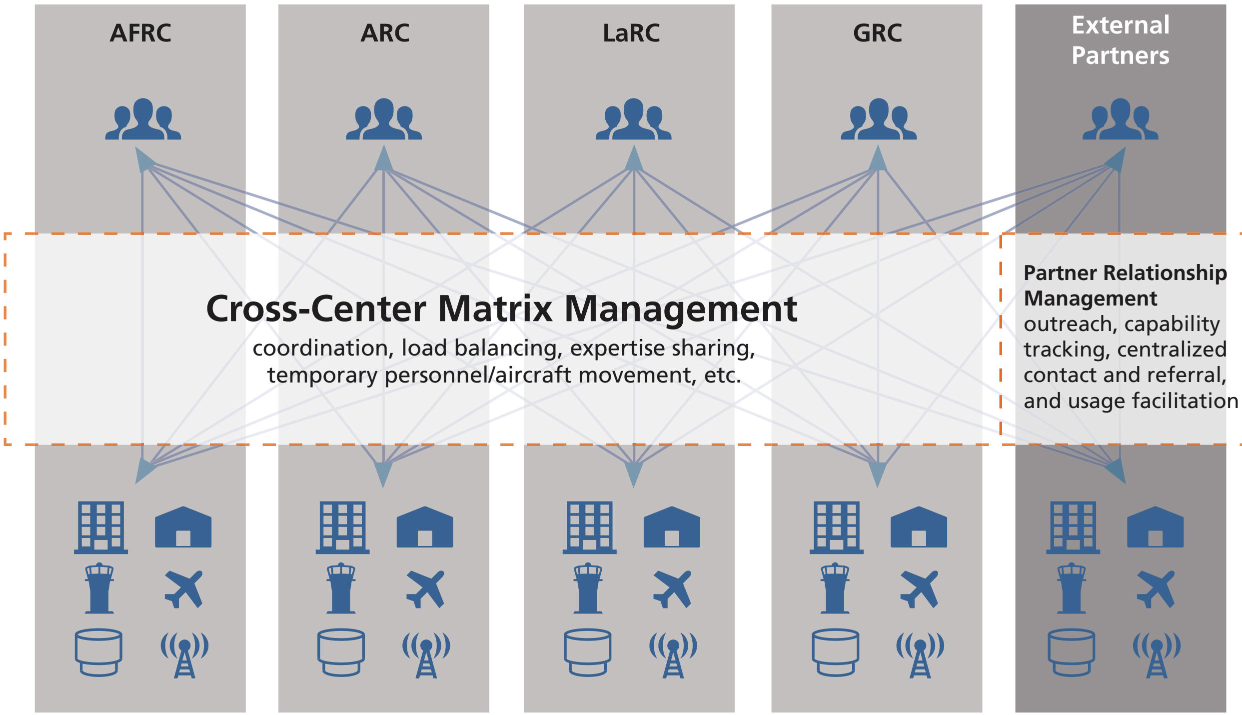
While facilitating cross-NASA utilization and efficiency, a matrix management structure would avoid the political problem of past efforts to centralize all flight research at a single location. The matrix structure would focus on advancing the coordination and sharing what ARMD has been pursuing, including participation and utilization of assets from multiple locations on research programs.

Perhaps as important, the matrixed organization could also serve as the central NASA organization responsible for flight research partnership information, outreach, and management. This function would facilitate tracking the capability of external entities, coordinate outreach, simplify contact and referral, and facilitate and simplify research program access and utilization of external capabilities and partnerships while providing coordinated advice on issues such as intellectual property decisions and international policies. Such a function could be performed by a new, separate office, but having it integrated with the internal matrixed organization would provide for a convenient "one-stop shop" and facilitate coordination between internal and external capabilities.

Further discussion of this MO, including implementation concepts and considerations, can be found in Appendix B.

Potential positive effects: Implementing this MO could reduce cost by eliminating some nonrecurring overhead, reducing management redundancies, and facilitating strategic prioritization, and therefore freeing up funding for research. It could also improve schedule and technical performance through streamlined access to capabilities across NASA and with external organizations and partners, improving the efficiency of outreach and coordination. Schedule risk should not increase if implemented correctly.

Figure 4.1
Cross-Center Matrix Management Structure (notional)



RAND *RR1361-4.1*

Potential negative effects: Excessive consolidation and centralization risks reducing access and responsiveness at the local level, particularly for relatively dynamic and lower-cost areas such as UAS research that benefit from experimentation with a diversity of approaches.

Effects on other stakeholders: Generally, the external effect should be positive. External users and potential partners would have a central point of contact within NASA, which could greatly facilitate communication and reduce cost.

MO-10: Explicitly Balance and Manage Risks

Motivation: Research inherently involves risks. These interrelated risks affect longer-range planning regarding portfolios, budgets, schedules, and infrastructure utilization. Risk-management techniques could help improve ARMD's strategic planning and ultimately the results of flight research.

Who would approve and direct the implementation of the MO? The associate administrator for aeronautics and supporting strategic planning staff would be responsible for approval.

Who would implement the MO? ARMD strategic planners, with support from research managers would handle implementation.

Implementation steps: Identify the kinds of risks that ARMD is subject to, then prioritize the leading risk types for further analysis. Review existing risk literature for appropriate methodologies, considering adaptations as needed.

Rough level of effort: Moderate to high. The effort involved depends on the types of risks to be addressed. Initial investigations, however, could be modest, exploratory research endeavors aimed at developing efficient, practical approaches for augmenting existing strategic efforts.

Discussion: Flight research is subject to interacting execution risks affecting cost and schedules. Research may be delayed or even prevented by capability gaps, capacity limits, and incentive mismatches between capability providers and capability users. Inefficiencies due to fluctuating demand that result in unutilized or underutilized capabilities can adversely affect program budgets and lead to delays and even collateral effects on other programs. Explicitly and effectively balancing such risks across all elements involved in flight research (aircraft, airspace, ranges, ground infrastructure, and workforce) in a way that is robust with respect to uncertainties in strategic planning, future budgets, and capability availability and demand promises to increase flight research efficiency. Such an effort would benefit from making explicit the key dependencies and risks involved in flight research management, and would have to be regularly updated and adapted to changing circumstances. However, while safety procedures—like other processes—should evolve and adapt to the changing flight research environment, safety levels should be considered nontradeable during any risk-balancing efforts.

Taking workforce issues into account as part of this balancing effort also means considering the long-term benefits of designing and building prototype vehicles. Even though this can be more costly than doing flight research using existing testbed aircraft, engaging in systems design—even at small scales—provides an opportunity to gain experience and hone skills that are of importance to a well-balanced aeronautics research workforce.

Balancing could also mean an increased emphasis on doing flight research on UAS, due to generally lower cost and higher risk tolerance. The current X-56 effort is one step in this direction.

A number of risk-management approaches could be employed to explicitly consider risks and their consequences in ARMD's strategic planning and decisionmaking. Some approaches use portfolio simulations to recommend sets of investment portfolios that maximize utility relative to larger strategic goals given the uncertainty of project success (for example, see Davis et al., 2008, and Chow et al., 2011). Other approaches consider explicit risk trade-offs, such as examining the effect of reduced backup aircraft (and thus reduced fleet costs) in exchange for schedule risk on research projects (see MO-11); such trade-offs may be considered in times of restricted budgetary resources. In addition, the budgetary prioritization option (MO-04) would identify projects that are at the margins of funding certainty and thus have higher funding risks. Explicit identification of those risks should lead those projects to explicitly develop risk-mitigation plans for how they would handle budgetary instability and the effect of that instability on infrastructure investments needed for their research. For example, those projects might be more willing to trade schedule for reduced costs or, alternatively, consider using supporting infrastructure that might cost somewhat more but have shorter lead times and greater flexibility in availability.

It was beyond the scope of this effort to examine specific risk types and relevant management approaches, but follow-on exploratory efforts could be pursued.

Potential positive effects: Implementing this option would encourage explicit, well-considered trades between cost reduction and increased schedule risk.

Potential negative effects: Balancing could lead to schedule delays if cost is overprioritized.

Effects on other stakeholders: Negligible. This is an internal NASA ARMD strategic planning option.

MO-11: Trade Schedule Risk for Cost by Adjusting the Number of Backup Aircraft

Motivation: Flight research managers often prepare backup chase aircraft to help ensure availability for flight research experiments. Risk analysis can be conducted using existing reliability data to estimate cost versus schedule risk if the number of backup aircraft were to be increased or decreased.

Who would approve and direct the implementation of the MO? Investment and divestiture decisions involve multiple stakeholders, including the Aircraft Advisory

Committee, center directors, and the Associate Administrators for Aeronautics and other mission directorates.

Who would implement the MO? Center flight operations managers and analytic support staff would handle implementation.

Implementation steps: Center flight operations managers would provide more-detailed historical data on aircraft availabilities and needs to analytic support staff. Illustrative calculations based on historical data are discussed below, but these would have to be revisited with updated availability data and detailed cost data.

Rough level of effort: Modest to moderate. The calculations themselves are fairly straightforward statistically, but, depending on how realistic the estimates need to be, significant data collection and analysis on availabilities and maintenance costs would need to be conducted.

Discussion: NASA's flight research enterprise has already significantly reduced its fleet of flight research aircraft over the past decades, to a total of 64 that met the "capital asset" threshold at the time of this writing, and further reductions are being considered. Especially (but not only) when budgets are tight, considering additional adjustments could help ARMD management to focus its resources on the most-promising flight research. Note that like several of the other MOs, MO-11 cannot be implemented by ARMD alone, because it would affect NASA center and NASA HQ assets and roles.

Reducing the number of backup chase aircraft would trade increased schedule risk for cost reductions through reduced infrastructure redundancy. NASA currently owns and operates several aircraft mainly used as chase aircraft that allow close-up in-air observation of research aircraft. This capability is important both for safety reasons (the pilot or observer in the chase aircraft can, for example, warn the pilot of the research aircraft if anything looks out of the ordinary) and for gathering research data (through sensors carried by the chase aircraft). The type of chase aircraft required for a given sortie is mainly determined by the flight profile that the test aircraft is executing. For example, if chase is required for a supersonic test flight, a high-performance chase aircraft has to be used. Furthermore, chase aircraft performance has to be above what is required to reach test points, since the chase aircraft needs to be able to maneuver around the test aircraft.

The chase aircraft fleet is sized to have backup aircraft available in order to reduce the potential for delays should one of the aircraft be inoperable when needed. The number of backup aircraft that are kept available might be reduced in order to save cost of ownership at the expense of possible schedule delays when vehicles are offline for maintenance.

To provide more detail for this option, we examined how reducing the size of the support aircraft fleet could affect the likelihood of delays for flight tests that depend on those aircraft for data collection or safety chase. Probabilistic analysis illustrates how aircraft availability (and thus, on-time execution of the associated research flight) is determined by the number of spare aircraft available. We use recent data on the reliability of the aircraft in ARMD's Support Aircraft and Maintenance Operations (SAMO) fleet at AFRC to estimate the effect of removing various types of support aircraft.[8] Table 4.4 lists the types of support aircraft in the SAMO fleet with their numbers and their fleet availability rates during FY 2012 and FY 2013.

This analysis is based on several assumptions:

- Based on recent experience, AFRC sustains a high enough capability to maintain these aircraft so that, on average, 85 percent of the relevant maintenance resources are committed to maintenance during any period. This level of utilization is close to full-time normal aircraft maintenance activity in the Air Force. We assume that, when an aircraft is removed, maintenance capacity is scaled down appropriately, as this is required to realize the savings associated with removing an aircraft.[9]

Table 4.4
Availability Statistics for SAMO Aircraft

Aircraft Type	FY 2012 Fleet Availability (%)	FY 2013 Fleet Availability (%)	Number of Aircraft in Fleet	Low Fleet Availability Rate (%)	High Fleet Availability Rate (%)
G-II	100.0	97.3	1	97	100
T-34C	100.0	99.2	1	99	100
B-200	98.5	94.7	2	95	99
F-15	66.1	84.4	2	66	84
F-18	96.1	90.6	3	91	96
Average	90.8	91.8	—	91	92

SOURCE: Horn, 2014, chart 22

[8] We use a simple model with simplified data to make a conceptual argument. With data on the reliability of each unique aircraft in the SAMO fleet, analogous modeling could be used to develop a more realistic estimate of effects. Such estimation would yield results that differ in the details, but look qualitatively similar. More-detailed analysis, for example, might be used to assess the incremental value of each unique tail number and, in the process, the potential desirability of mothballing or divesting a specific tail number. Time is another factor that could be taken into account for enhancing this kind of analysis, since the timing of when a failure is detected, along with the time needed for repairs, drives availability. To determine the likelihood that a support aircraft will fail in a time period that will cause delay requires information on the "time to failure" distribution of the aircraft. Exponential, Weibull, and variations of normal distributions are often used in reliability models where the interest is the time until a system or component fails. (Ross, 2007; Pascovici et al., 2008)

[9] Detailed information on the organization and cost of maintenance is needed to determine how much cost would fall if the demand for maintenance services was reduced. For example, it is possible (but highly unlikely) that costs would not fall at all. This could occur if each worker has unique skills that are necessary for effective maintenance, and none of the workers are active 85 percent of the time. Such unique and necessary skills create scale economies in most aircraft maintenance activities that limit the importance of variable costs. To understand what costs could be removed by eliminating an aircraft, NASA would need to map the specific maintenance demands of the aircraft against the skills of the labor force in the maintenance shop. Tools are available to structure such analysis. For example, the Dyna-METRIC model in Hillestad (1982) was developed to study and predict the readiness of groups of aircraft squadrons as determined by a major subset of logistics resources—namely, those associated with component repair and resupply.

- We assume that aircraft of the same type are interchangeable with each other for the purposes of the chase/safety mission.
- Based on information from NASA, we also assume that, to the degree possible, more support aircraft are prepared for each test flight than the number actually needed, to mitigate against last-minute breakdowns.
- Finally, the analysis assumes that the availability of aircraft behaves as though the breakdown rate—or nonavailability rate—for each aircraft is binomially distributed. Table 4.5 shows the resulting relationships between the number of support aircraft that are prepared for a flight test and the number of support aircraft that are ultimately available, based on the probability p of an individual aircraft experiencing an unexpected breakdown prior to the flight test (i.e., a prepared aircraft not being available).

For example, suppose AFRC wants to prepare two of the same type of aircraft to ensure that at least one is available for a given flight test. Per Table 4.5, the probability for this is $1–p^2$. If we observe that SAMO's fleet of two B-200s can support flight tests 95 percent of the time (see Table 4.4), this means $1–p^2=0.95$ and, consequently, $p=0.22$. Thus, each individual B-200 has a $1–p=1–0.22$, or a 78-percent chance of being available following preparation. Now, if we remove one aircraft from the B-200 fleet, and thus only one aircraft can be prepared for the test, the probability of having "at least one" aircraft available following preparation is $1–p=0.78$. Hence, removing one B-200 reduces the likelihood that a B-200 can support the test flight from 95 percent to 78 percent, or by about 17 percent.

We can repeat this thought experiment for the other aircraft in the SAMO inventory. Table 4.6 summarizes the effects of such a removal for the B-200, F-15, and F-18 fleets.[10] Removing one aircraft cuts SAMO's likelihood of being able to support a test flight with the designated type of aircraft by 8 to 36 percent, depending on the aircraft removed. Not surprisingly, the size of the effect depends on the reliability of the aircraft of each type, and on the number of aircraft in the fleet. The higher the reliability

Table 4.5
Relationship Between Number of Aircraft Prepared and Number Available with a Binomial Distribution of Failure

Number of Aircraft Prepared	Number of Aircraft Available						
	0	1	2	3	4	≥1	≥ 2
1	p	$1-p$				$1-p$	0
2	p^2	$2(1-p)p$	$(1-p)^2$			$1-p^2$	$(1-p)^2$
3	p^3	$3(1-p)p^2$	$3(1-p)^2p$	$(1-p)^3$		$1-p^3$	$3(1-p)^2p+(1-p)^3$
4	p^4	$4(1-p)p^3$	$6(1-p)^2p^2$	$4(1-p)^3p$	$(1-p)^4$	$1-p^4$	$1-p^4-4(1-p)p^3$

[10] Because SAMO has only one G-II and T-34C each, they were not considered in this analysis.

Table 4.6
How Removing One Aircraft Reduces SAMO's Ability to Support Flight Tests

	Before Reduction		After Reduction		
Type of Aircraft	Number of Aircraft	Likelihood of at Least One Aircraft Being Available (%)	Number of Aircraft	Likelihood of at Least One Aircraft Being Available (%)	Degradation in Likelihood of Availability (%)
B-200	2	95–99	1	78–90	9–18
F-15	2	66–84	1	42–60	29–36
F-18	3	91–96	2	81–88	8–11

of an individual aircraft in a fleet, and the more of that type there are, the smaller the effect of removing one aircraft.

Analysis like that presented here, especially if based on more-detailed data for the reliability of each unique tail number in the fleet, could support decisionmaking on potential fleet size reduction options by helping balance cost of ownership against the risk of potential schedule delays. However, the latter can be mitigated to a degree by reducing the amount of flights for which chase planes are needed. On the other hand, high-speed chase aircraft are also used for pilot proficiency flights (see Table 4.2), which will have to be taken into account in this context; furthermore, some scenarios require more than one chase aircraft per research flight, which would affect the above calculations.

Potential positive effects: Reducing the number of (or at least ARMD subsidies to) aircraft mainly used as chase aircraft would reduce fixed nonrecurring and recurring costs.

Potential negative effects: Fewer backup aircraft being available would increase schedule risk, because aircraft may not be ready when needed. This particularly affects research portfolios that emphasize supersonic research, since some supersonic chase aircraft have lower reliability rates compared with subsonic aircraft (and thus are more likely to be unavailable; see Table 4.4), and are less likely to be available for acquisition on short notice in case inoperable aircraft need to be replaced.

Effects on other stakeholders: The primary stakeholder effects are on the research programs themselves, wherein the balance between cost and schedule risks might be changed if backup aircraft numbers are increased or decreased.

MO-12: Institute a Voucher System for Short, Exploratory Flight Research

Motivation: A certain amount of research aircraft flights must be conducted every year to maintain pilot proficiencies. In our interviews, we found that pilots and local managers often offer these flights to researchers for free, but we found no strategic process for prioritizing such activities. A more formal system to strategically allocate such resources could ensure that time goes to the most promising research, including consideration of external users who may have promising innovative ideas that would benefit from even relatively small amounts of flight testing.

Who would approve and direct the implementation of the MO? NASA leadership, including the associate administrator for aeronautics and center directors, would be responsible for approval.

Who would implement the MO? Center flight operations managers, or coordinators in a matrix management structure (MO-09), would handle implementation.

Implementation steps: Identify the amount and type of flight resources available for the voucher system (including existing proficiency flights and any additional institutionally funded flights that ARMD might want to include). Establish a set of selection criteria and delineate the requestor pool based on leadership input. Establish a request process, possibly in conjunction with the annual user survey (MO-08) or using SMD's Science Operations Flight Request System (SOFRS). Establish a selection board (which could reach across NASA through the matrix managed structure, MO-09) and select voucher recipients.

Rough level of effort: Modest to moderate. The exact level of effort would depend on the scope of the resources and selection criteria involved—a pilot program (e.g., based on a single center such as AFRC) would make sense to explore options and generate feedback.

Discussion: Assigning a number of flight research hours (for example, in the tens of hours) to each ARMD program for use by researchers, at no additional cost, on smaller, less-complex flight research projects (including instrumentation development), similar to how time on some of NASA's supercomputers is allocated, could encourage more researchers to test innovative ideas and investigate new concepts. Flight hours could be combined with those needed for mandatory pilot proficiency training to reduce the amount of additional funding required. This would make good use of capability availabilities between major scheduled projects and could be a mechanism for more-transparent allocation of research opportunities on already-paid-for pilot proficiency flights. Such an effort could also be expanded to include researchers outside NASA (e.g., in academia) who may have concepts that would benefit from small amounts of flight research but who do not have sufficient funding. For example, many academics use remote-control aircraft to test aeronautics concepts; a voucher system would allow them to scale their concept to large UAS or manned aircraft and conduct preliminary tests in just a few hours to get valuable data on whether their concepts are promising. However, in order to maximize the benefits of this approach, care should be taken not to unduly favor current project partners or other quasi-insiders, while at the same time ensuring that valuable flight research resources are only spent on truly promising, innovative research. This will require instituting a transparent and effective vetting process for proposed projects.

Funding for this should come from ARMD directly, from a level not lower than the programs, to avoid "pass-through taxes." Of course, supported research should be aligned with ARMD priorities, but proposals can also be seen as an indicator of where the research community is going (MO-08). Examples of similar approaches for allocating free test resources include NASA's High-End Computing Program, which allocates supercomputing time to researchers on a request and competition basis (NASA, 2013b), and NASA's Innovative Advanced Concepts (NIAC) Program, which supports early, exploratory research (NASA, 2016c).

Potential positive effects: This approach would facilitate executing simple but nevertheless potentially highly valuable flight research, thus reducing process times (MO-13) and cost to the researcher while increasing benefits relative to cost. Furthermore, it would allow researchers to gain experience with and understand the value of flight research, thus possibly leading to funded follow-on flight research efforts. It might also lead to full-fledged collaboration projects (MO-05).

Potential negative effects: Diverting some ARMD funding toward "simple" flight research could lead to a loss of focus and, above a certain level, would reduce funding for more-complex efforts.

Effects on other stakeholders: This voucher system could have a significant positive effect on researchers who have few resources but promising ideas (e.g., in academia). Of course, researchers that are benefiting from free flights under the current system would have to compete under the new process.

MO-13: Streamline the Process That Researchers Must Use to Obtain Flight Research Capabilities

Motivation: In discussions with NASA researchers and center flight operations managers, we found that there is no well-documented, transparent process for aeronautics researchers to request flight research capabilities, which creates a barrier to entry for flight research.

Who would approve and direct the implementation of the MO? NASA leadership, particularly the associate administrator for aeronautics and center directors, would be responsible for approval. If the matrix management structure (MO-09) were implemented, then this MO could be approved and directed by that organization.

Who would implement the MO? Center capability managers, or coordinators in a matrix management structure, would handle implementation.

Implementation steps: Review existing processes. Collect user feedback and generate requirements for the new process. Assess potential of using existing systems; e.g., SMD's SOFRS. Consider implementing an initial pilot for a single location's set of assets before full-scale rollout.

Rough level of effort: Modest to moderate. The level of effort will depend on how much process development is needed.

Discussion: More-transparent and more-responsive processes for planning and scheduling flight research activities can draw more researchers to flight research while reducing overhead. This could include identifying and eliminating unnecessary procedural hurdles, and/or providing a central web portal that researchers can use to identify and request suitable test aircraft (for example, see the SOFRS website developed for airborne science research by NASA's SMD [NASA, 2015e]), as well as ground-based capabilities. Such a portal could show the available aircraft and their known or planned utilization, and it could also provide a simple intake form where researchers from inside and outside of NASA who are interested in performing flight research at NASA can make their needs known (MO-08).

It could also involve designating single points of contact who can help researchers navigate the required processes and paperwork (for example, the approach used by DLR and the matrixed organization idea outlined in MO-09) and who can build networks of support across centers. Furthermore, outfitting additional aircraft with standardized payload interfaces would facilitate integration of some flight research payloads. Finally, an annual (or more frequent) event that introduces center researchers to flight research capabilities across NASA and provides related updates would be another step in this direction, and would also help build the awareness needed to fully implement MO-01.

Potential positive effects: Streamlining would reduce schedule risk and create time savings for researchers. Furthermore, more researchers might consider flight research, which would bring in more funding.

Potential negative effects: Implementing this option would incur some (albeit modest) cost.

Effects on other stakeholders: This could have a significant positive effect on researchers at the planning and operational level. These benefits would extend to users outside NASA if expanded to include them as customers.

MO-14: Improve Access to Flight Research Data for Researchers

Motivation: We found no easy-to-access central repository for flight research data. Existing NASA archives either contain summary research papers or are hard to access even for validated users. Direct access to raw flight research data would increase the impact of flight research.

Who would approve and direct the implementation of the MO? NASA leadership at the HQ and center levels, including the Chief Information Officer (CIO), would be responsible for approval.

Who would implement the MO? Staff from the CIO office in collaboration with center knowledge managers and researchers would handle implementation.

Implementation steps: Survey types and quantity of data that would have to be stored, including associated access control measures, and collect researcher input on how such a repository would be used. Develop an implementation plan and schedule, including cost estimates. Select infrastructure and set up database, interfaces, and access-control measures.

Rough level of effort: Moderate. The NASA CIO is already contracting with Amazon Web Services (AWS) GovCloud for sensitive (restricted via International Traffic in Arms Regulations [ITAR]) data storage. Database maintenance and account management would likely require full-time staff.

Discussion: Currently, NASA flight research data are neither centrally stored nor readily accessible to the U.S. aeronautics research community outside those directly involved in a specific research project—certainly not to the degree that NASA data and old NASA Technical Reports were made available. Therefore, this option entails improving the storage and archiving of flight research data and derived results, facilitating U.S. researcher access to that data in order to increase the value that can be extracted from existing flight research, inspiring new research ideas and associated flight research requirements, and helping avoid redundant testing.

At least some of these data are export controlled via ITAR or Export Administration Regulations (EAR). Others include data that is proprietary to external research companies involved in the research. As a result, the system would need to be restricted access–capable (e.g., password-protected accounts for specific individuals who have access depending on their nationality and institutional affiliations).

Images and video should be included, as well as other sensor data. Complete documentation and metadata, including systematic and thorough tagging, would be required for all data sets to provide the necessary context and search capability; simply storing the raw data is insufficient. Issues of long-term knowledge management and digital obsolescence would have to be addressed as well. This system would have to support different levels of access—from fully public to closely held—in order to accommodate varying levels of data sensitivity, similar to DoD's knowledge dissemination infrastructure.

Beyond institutional funding for establishing and maintaining the required information technology infrastructure, including paying for storage after a project has ended, this also means requiring all projects to set aside sufficient funding to make data available, including funding for the labor needed to add the necessary metadata. Efforts along these lines are already under way at AFRC.

Implementing this MO would directly support the recent OSTP requirement—and associated guidance from NASA HQ—on sharing NASA research results to the degree possible (OSTP, 2013; NASA, 2014a). It would require providing flight researchers with specific guidance on what data they would be expected to share and how to create a data management plan supporting it; for an example, see the NASA SMD ROSES Mission Data Management Plan (NASA, 2015b).

NASA is moving to the private AWS GovCloud for storage of protected and ITAR data (Gaudin, 2014; Boyd, 2015). It is beyond the scope of this study to assess the volume of flight research data that NASA generates, data architecture options, preferred approaches and plans of the NASA CIO, and negotiated NASA prices. However, to provide a sense of the costs involved, the current list price on AWS GovCloud for "Standard—Infrequent Access Storage" is \$0.02 per gigabyte per month, with access fees being charged separately (see AWS, 2016). For this example, if a project were to generate ten terabytes of data—the capacity of several hard drives—that needed to be archived, this would result in storage charges of $2,400 per year.

Potential positive effects: Improving access can save cost and time needed for finding and accessing relevant flight research data. It can also reduce the amount of repetitive flight testing that is needed (if relevant data are available from past flights) and thus reduce overall cost, as well as schedule and safety risk. Implementing this option would also benefit NASA's "public good" mission.

Potential negative effects: While investments in infrastructure and staff time for an improved data storage and dissemination infrastructure should be modest, they are not zero. In particular, data would have to be reviewed for export control and other issues, and the knowledge management system/infrastructure accordingly would have to support varying levels of access, as well as an increased volume of queries as the service becomes more popular.

Effects on other stakeholders: Direct access to raw data could advance flight research across NASA, DoD, industry, and academia (as appropriate given data access restrictions).

V: Advocating for Additional Funding

The most straightforward approach to increasing flight research might be to further increase the overall ARMD budget and, with that, the funding that can be made available for flight research.

MO-15: Articulate Benefits, Especially in Monetary Terms, to Explain Their Value

Motivation: We found that many aeronautic research successes are often expressed in technical terms, and thus their potential social and economic benefits are hard for nonexperts outside the aeronautics community to gauge. This can make it difficult to justify increased flight research to Congress, OMB, and the public. Past NASA efforts to translate value into monetary and social terms have been useful but could be expanded.

Who would approve and direct the implementation of the MO? The associate administrator for aeronautics would be responsible for approval.

Who would implement the MO? ARMD project and program managers would handle implementation.

Implementation steps: From project proposals, extract estimates of the kind of benefits that could ensue if the research is successful, how flight research plays a role, and a rough estimate of the research and subsequent maturation costs to realize the benefits. Assess the viability of monetizing the benefits (both practically and in terms of credibility) and—if deemed viable—perform the necessary calculations.

Rough level of effort: Modest.

Discussion: As discussed earlier, NASA funding ultimately depends on convincing external decisionmakers that the taxpayers' money is put to good use. Unfortunately, benefits from aeronautics are hard for nonspecialists to put in perspective and compare with costs when expressed in direct terms. Thus, whenever possible, NASA should continue to explain potential benefits in both domain and monetary terms.

Perhaps the most direct approach to justifying increased flight research is to describe its relative value as ROI. In addition to explaining the potential benefits in qualitative terms, monetized estimates should be provided to help offer perspective and direct comparison with costs. ROI-based requests are strongest when they apply to current and future activities; while historical reviews of success in aeronautics (e.g., Bilstein, 1989; Bargsten and Gibson, 2011; Launius and Jenkins, 2012) are insightful, there is no guarantee that continued investments will yield similar benefits.

Here we use the term "ROI" in the broader sense of describing value as the potential beneficial returns relative to estimated costs. There are different ways to numerically demonstrate a return, including formal ROI calculations, net present value, and internal rate of return calculations. Government calculations are dictated by Circular A-94 (OMB, 1992), which specifies net present value and benefit-cost analysis (BCA) procedures, discount rates, treatment of uncertainty, and other considerations. While BCA can be difficult to conduct for research, these approaches could be used in NASA's socioeconomic impacts analysis (NASA, 2014b) to compare costs with the benefits cited while further clarifying the benefits to external audiences. For example, ARMD estimated that ATM concepts from NASA, the FAA, and airlines led to $1,700 savings per flight (NASA, 2014b), but how many flights, over how many years? Also, there was no indication of the R&D and implementation cost of those concepts, or an assessment of what the trends or other implications might have been without them. Likewise, the $300 million in estimated savings related to better management of aircraft operations near congested terminals (NASA, 2014b) lacked an estimate of the associated R&D and implementation costs, and it did not state whether the savings were annual (recurring) or total. In other examples, the benefits cited were not expressed in monetary figures that could be compared with R&D costs, or expressed in other ways to improve perspective, even when that would have been easy to accomplish. For example, the four billion gallons in jet fuel saved cited in the study (NASA, 2014b) could have been converted to a dollar value; i.e., $11.4 billion at the 2014 fuel cost of $2.85 per gallon (Bureau of Transportation Statistics, 2015). NASA also could have indicated whether this saving was total savings or annual. In addition, the reduction of 43 million tons of carbon dioxide can be monetized as representing $1.8 billion in social costs using published government guidelines for the social cost of carbon dioxide.[11] Presenting both the explanation of what the benefits are (43 million tons of carbon dioxide along with why those reductions might ensue) plus the monetary value ($1.8 billion) better informs nonspecialists of the costs and benefits of NASA's research. These figures can

[11] The Environmental Protection Agency estimates the social cost of carbon dioxide to be about $41.15 per ton of carbon dioxide in 2015 dollars (Bureau of Labor Statistics, undated; Environmental Protection Agency, 2015).

then be used in standard BCA calculations, but it is important to provide the background explanations and figures, not just a table of numbers that can seem meaningless or arbitrary without the supporting descriptions.

Of course, it is not possible or practical to monetize every potential benefit—either because they have no clear monetary equivalence or because such estimates would be highly speculative and controversial. For example, an estimate of the monetary benefit of a commercial supersonic aircraft market could be extrapolated from the prior supersonic transport aircraft experience, but that market was significantly constrained to overwater travel and the aircraft has significant inefficiencies. Thus, estimating that potential benefit in monetary terms might draw more criticism to the analysis and distract from the central discussion about the merits of the research. Nevertheless, adding monetized equivalents of benefits (as with the examples above) will help inform discussions with stakeholders.

A more qualitative approach to arguing for an increased budget would involve engaging in research that may have a strong appeal to Congress and the public. For example, pursuing more revolutionary and innovative concepts could increase interest. Current and past examples include novel uses of UAS, personal air vehicles, electric propulsion, and new concepts for vertical and/or short take-off and landing. NASA ARMD is involved in some of these areas, but despite ARMD efforts they still have relatively low visibility in the broader public and many have not resulted in high-visibility commercial products.[12] Getting revolutionary aeronautics technologies ready for commercial implementation requires flight research, but that requires a larger budget. This approach is no guarantee of success, of course. Such R&D still needs to have a clear value, be practical, and (often) have a rather short-term benefit. Even the Defense Advanced Research Projects Agency periodically faces budgetary reductions, despite their reputation for pursuing high-risk, high-payoff, revolutionary concepts.

Potential positive effects: At the national level, monetized benefit analysis helps increase funding for efforts with positive value propositions that will benefit the U.S. economy and contribute to the public good. For ARMD, if aeronautics research funding is expanded, then flight research can be expanded as well. Side benefits will also ensue, such as lowering the fixed nonrecurring costs of maintaining unique flight research capabilities by spreading them across a larger user base.

Potential negative effects: Expanding BCA and promoting the results will incur a certain cost, mainly in labor, and credible monetization of benefits will not be possible for some research areas.

Effects on other stakeholders: This effort could greatly help OMB, Congress, and the public understand the potential value of aeronautics flight research (and aeronautics research in general).

[12] R&D efforts can still be valuable even when they do not result in a specific, commercialized product. Investment in new ideas is important to drive innovation, even if many of them do not work out.

Other Management Options Examined

In addition to the 15 MOs discussed above, we examined the following three additional options in our initial set. However, they were not included in our further analysis and discussion with our SMEs for the following reasons.

Outsourcing Management of Flight Research Infrastructure. There was insufficient evidence to recommend outsourcing the management of all of NASA's flight research assets to a commercial provider (i.e., in a government-owned, contractor-operated [GOCO] arrangement, somewhat similar to the UK Ministry of Defence [MOD] model mentioned in Appendix A). While the study team was not chartered to conduct a detailed management review of center-level flight research operation, comparisons (e.g., rates per flight hour or sortie) indicated that NASA management has been fairly efficient compared with external operators. Thus, it is not clear that there is a compelling reason to outsource on the ground of inefficiency, and further analysis would be needed to estimate whether contractor operation (for-profit or nonprofit) would be more efficient and cost-effective. Also, outsourcing that involves consolidation at a single site might meet with the same kind of congressional resistance that NASA met in past efforts to consolidate internally. Thus, we chose to continue analyzing the more incremental option. Wholesale outsourcing might be a consideration in the future if continued efforts to integrate and improve cooperation succeed. Like the UK MOD model discussed in Appendix A and current struggles in the United States with GOCO models (e.g., the for-profit management of Los Alamos National Laboratory [Kramer, 2016]), these actions require significant strategic leadership involvement, planning, and action.

Leasing Aircraft at Need. Another option we initially considered was for NASA to lease aircraft at the time a project needs them, rather than owning them. Leasing subsonic aircraft may be possible for certain chase aircraft if significant structural modifications are not required (e.g., if a camera or sensor can be temporarily mounted near a window without major structural modifications that would be unacceptable to the owner). However, leasing is not viable for testbed aircraft (because they usually require major modifications) or supersonic aircraft (because generally they are not commercially available for lease). Thus, while leasing is possible and might be considered on a case-by-case basis (e.g., as a surge capability option when major modifications are not required), we determined that this was not a major MO.

Outsourcing to Flight-Test Service Organizations. An additional option we initially considered was for NASA to contract for flight testing as a service. Outsourcing to external flight research organizations may be possible but only in limited cases. While there are no direct statutory or regulatory barriers to direct commercial outsourcing, NASA's direct flight costs already appear low enough that any cost savings might be offset by increased expenditures for safety oversight, contract administration, and contractor profit. Based on experience from past attempts at outsourcing, NASA would also face the challenge of having to ensure that performance is well specified and incentivized in contracts. There are a few domestic providers that could be considered, but they cannot replace NASA, since most flight research organizations are relatively specialized in the type(s) of aircraft at their disposal, whereas NASA has access to a more diverse fleet that also includes higher-speed regime aircraft. NASA also manages larger and more-diverse pools of personnel and laboratories than any single external organization that we observed. Moreover, NASA's regulatory authority for experimental flights is unique and applies even in cases of a commercial flight research provider. NASA does regularly contract for commercial aviation services (CAS); however, in recent years those have been for airborne science and spaceflight support missions, not for aeronautics research, and they have been a small fraction of overall NASA flights (about 500 flight hours out of more than 10,000 total flight hours for each of the past several years—see NASA, 2015a). Furthermore, risk analysis performed by NASA's AMD has identified CAS oversight and management as an area that needs to be strengthened even at the current level of activity, citing "instances of CAS use by NASA centers without appropriate review" as well as "quality and workmanship issues" (NASA, 2015a, p. 47). Commercial for-profit entities may have greater incentives to accept higher safety risks than government organizations may find acceptable.

As for potential governmental service providers, DoD is the best candidate. However, DoD does not appear to have readily available excess capacity, and it focuses more on developmental testing than on research testing.

Some of the national flight research organizations of allied countries maintain capabilities that NASA does not have, and collaboration as well as partnering can therefore be a viable option (MO-05 and MO-06). However, full outsourcing to international organizations would require NASA to accept significant risk and introduce political complexities, given that NASA is chartered in part to improve U.S. competitiveness (NSTC, 2006).

Finally, outsourcing would probably entail some long-term reliance on the service provider (unless, of course, the capabilities in question are only needed for a specific research project). NASA has had long-term partnerships in the past, such as with the U.S. Army on rotorcraft research. But it should be remembered that the last decade's budget environment has affected even these federal partnerships; the partnership with the U.S. Army mentioned earlier was only one casualty. Long-term partnerships require long-term funding and stability. While not impossible, we found no obvious candidate for outsourcing to date.

CHAPTER FIVE

Assessment of Management Options

We assessed the potential impact and relevance of all 15 MOs introduced previously. General advantages and disadvantages were included as part of the discussion of each MO in the previous chapter. Due to sponsor interest, one of the options (MO-06, "Increase Partnering") is assessed in detail in this chapter. We also discuss potential synergies between MOs, and close with a summary of how our panel of SMEs rated the MOs.[1]

Scenario-Based Assessment of the "Increase Partnering" Management Option

As requested by ARMD, we analyzed the "Increase Partnering" MO (MO-06) in particular detail, given that NASA has made and continues to make use of partnering in flight research, and partnering provides alternative sources for obtaining needed capabilities. These capabilities can be arranged in four categories:

- technology: subject-matter expertise, intellectual property, equipment
- flight research aircraft: unmodified, slightly modified, or demonstrator
- support aircraft: chase planes
- safety/range: safety review, flight test range sensors and operations.

All four aspects are important to recognize when examining partnering, as each plays an important role in flight research.

[1] RAND convened a panel of six senior SMEs to provide feedback on the MOs and share additional insights on the study topic. SME backgrounds varied, from a retired chief executive officer of a major aerospace company, to a former NASA center director, to a former test pilot. To foster candid discussion, the SMEs were assured nonattribution and are thus not quoted by name.

Scenarios and Baselines

NASA ARMD specified four scenarios to use in assessing this MO. The analysis includes the costs incurred to plan or sustain any required infrastructure, and for safety, engineering oversight, and any certification required for flight research.

The scenarios represent examples of past projects and those of plausible future work.

1. ACTE—a conformal trailing edge flap utilizing nonrigid wing flaps mounted to a large business jet–class aircraft
2. LBFD—supersonic transport technology research
3. UAS autonomy
4. Alternative Fuel Effects on Contrails and Cruise Emissions follow-on (ACCESS-II)—an evaluation of alternative biofuels on engine performance, emissions, and aircraft-generated contrails at altitude.

These scenarios were helpful in several ways. They assisted in the identification and assessment of alternative partnering arrangements. Using the four scenarios, the analysis captures the impact of partnering on cost and risks. An important assumption is that overall scope is not assumed to change between the partnering alternatives within each scenario. That is, adding or removing partners does not increase or decrease the overall scope of the work.

The baseline capability providers for the alternatives are shown in Table 5.1. Chapter Two presents additional background on the range of capabilities provided by various potential partners.

The LBFD baseline scenario calls for a piloted X-plane to be developed. This is assumed to be a NASA and industry partnership. The UAS studies reference scenario is a combination of NASA UAS, academia-provided UAS, and leased UAS. All these plans call for use of the DATR for safety purposes.

This analysis is being performed to assess the impact of different partnering arrangements on work that NASA has performed or could perform in the future. Rather than assess individual characteristics of partnering separately, the scenarios were developed to allow the research team to assess how the individual characteristics

Table 5.1
Scenario Capability Provider Baselines

Scenario	#1 ACTE	#2 LBFD	#3 UAS	#4 ACCESS-II
Technology	AFRL and industry FlexSys	NASA and industry	NASA	NASA
Flight test aircraft	NASA and AFRL	NASA and industry X-Plane	NASA	NASA
Support aircraft	NASA	NASA supersonic	NASA/leased aircraft	NASA/ NRC-Canada/DLR
Safety/range	AFRC/DATR	AFRC/DATR	AFRC/DATR	NASA

would interact in a realistic scenario. The four reference scenarios were derived from different levels of detailed data. Reference scenarios 1 and 4 are based on actual past projects and thus are well defined, have baseline records, and have some published results based on previous NASA research. Scenarios 2 and 3 are conceptual, although they were built using past and planned future work as a reference. Scenario 2 nominally has three phases over 15 years with demonstrator funding. Scenario 3 has six options over a three-year period with defined resources of $15 million total. The reference scenarios, as well as the alternate scenarios, are not necessarily fully representative of NASA's current or planned programs and projects.

However, they provide a useful framework for examining partnering alternatives and other MOs. Alternative arrangements change the overall cost, timeliness, and safety of the scenarios. The alternatives allow for a systematic assessment of alternative capability sources, which can illustrate partnering potential. Alternative partnering capability sources will be compared with a set of reference baseline capability sources, resulting in list of pros and cons with respect to time, safety, technical benefits, technology transfer, and intellectual property issues. Scenario analysis includes a rough estimate of cost differential.

The subsequent sections introduce partnering alternatives for each of the four scenarios, and discuss their respective advantages and disadvantages. In the tables, advantages are colored green while disadvantages are colored red. A white background means that no change would be expected for the individual characteristic. The ranking of the partnering options was performed by analysis and input from SMEs.

Scenario 1: Conformal Trailing Edge Flap Research

The ACTE flight program is a joint venture with AFRL and FlexSys, Inc. Over six months, as of April 28, 2015, 23 flights had taken place. The total aircraft cost estimates range from $676,000 to $809,000. Figure 5.1 shows the NASA aircraft, which was acquired with AFRL, and the FlexSys flap installed.

In FY 2015, ARMD plans called for using the Gulfstream G-III for ACTE research. The research plan was for 20–25 flights. Table 5.2 shows the sorties and hours for each aircraft type.

For future planning purposes, a wing test similar to ACTE will need 20–25 chase sorties; of those, 10–15 will utilize the high performance aircraft and 10–15 will use a lower performance aircraft, a Gulfstream G-II.

The teaming arrangement utilized in the ACTE tests involved sharing resources and test data between NASA, USAF, and private industry. The nature of the tests meant that the data were FlexSys intellectual property. If FlexSys had not been a part of the partnership, the data would likely have been publicly available, like NASA's other test data.

A series of partnering alternatives were designed to investigate how different flight test and support aircraft arrangements could affect an ACTE-like test. These alter-

Figure 5.1
NASA G-III with FlexSys Flap Attachment in Flight

SOURCE: U.S. Air Force Material Command, 2015.
RAND *RR1361-5.1*

natives will illustrate some of the pros and cons of changes in partnering arrangements. Table 5.3 shows the details of the baseline and the three partnering alternatives designed for a wing test.

Using the scenario details listed in Table 5.3, each of the items was rated in terms of safety, cost, time, and other. The ratings are shown in Table 5.4.

As the baseline scenario involves significant partnering with AFRL, which developed the technology and covered some of cost for the testbed aircraft, the first two alternative scenarios provide contrast to that partnering arrangement. The all-NASA and all-DoD alternatives primarily transfer the cost to one or the other, and the latter is projected to have higher total costs. In both cases, the benefits of partnering are lost. The third alternative proposes using less-capable support aircraft as chase planes to save money. In this

Table 5.2
ACTE Sorties and Flight Hours to Date

Actual Test Sorties and Hours for Total Project to Date (2012–2015)	Sorties	Hours
Test Aircraft (G-III)	37	105.1
High Performance Aircraft/ Fighter Chase (F/A-18 and F-15)	30	53
Jet Chase (C-20 and G-II)	4	17.3
Turbo Prop Chase (T-34)	1	2.4

Table 5.3
Scenario 1 Partnering Alternatives

Scenario	ACTE Reference Sources	All NASA	All DoD	Alternative Chase Aircraft
Technology	AFRL and industry FlexSys	NASA	AFRL and industry FlexSys	AFRL and industry FlexSys
Flight test aircraft	NASA/AFRL (G-III purchased for tests, acquisition cost split)	NASA (Would need to pay 100% acquisition)	USAF	NASA/AFRL
Flight test AC costs	$1.5 million NASA/ $500,000 AFRL	$2 million	$2 million	$2 million
Support aircraft	NASA	NASA	USAF	NASA subsonic
Support AC costs	$240,000 to $530,000	$240,000 to $530,000	$580,000 to $775,000	$42,000 to $130,000 (plus acquisition of more subsonic aircraft)
Safety/ Range	AFRC/DATR	NASA	USAF	AFRC/DATR
Comments	NASA modified the G-III test aircraft. Also included are 5 fighter chase, 1 jet chase, and 1 turboprop chase	Increases cost to NASA; might increase industry access to IP	Decreases cost to NASA	Potential to reduce cost to test program, but likely to increase the NASA total flight research capabilities cost

SOURCES: NASA, 2012; Office of the Undersecretary of Defense, 2013.

NOTE: Converted to FY 2015 dollars. Assumes 35 to 40 sorties. AC=aircraft; IP=intellectual property.

Table 5.4
Scenario 1 Rating of Partnering Alternatives

Baseline	Impact of Alternative Scenarios		
Reference Scenario	**All NASA**	**All DoD**	**Alternative Chase Aircraft**
Cost to NASA: No technology development costs, G-III test platform jointly purchased by NASA/AFRL, all flight test support aircraft costs	NASA absorbs full technology development and research aircraft costs	NASA no longer funding flight testing	Operational savings of $300,000 roughly equal to cost of acquiring/ leasing alternative chase aircraft
Costs to other government: Technology developed by AFRL and FlexSys, G-III test platform jointly purchased by NASA/AFRL	AFRL no longer responsible for technology development costs or share of flight research aircraft	Increases by $300,000 and all costs transferred to DoD	No significant change
Time: 15 years R&D, 1 year flight test	No significant change	No significant change	No significant change
Safety: Modeling due to aerodynamic modification of manned aircraft	No significant change	No significant change	No significant change
Other: Close DoD/NASA partnering	No partnering with DoD	No partnering with NASA	No significant change

NOTE: Green=substantially better; red=substantially worse.

particular scenario, the chase plane needs to match at least the research aircraft's altitude and speed envelope (i.e., the G-III flight envelope). Greater agility and speed allows the chase aircraft to fly closer and adjust position more quickly, which is assumed required for at least half the sorties. Assuming that ARMD support aircraft fighter jets (e.g., F-18, F-15) are only used when necessary, the remaining sorties can use a less capable jet aircraft (e.g., T-38, G-II.) While the direct costs for the support aircraft might decrease for the test series, the overall cost to NASA could increase due to the cost of acquiring and maintaining additional aircraft, given the fixed costs of maintaining additional types of aircraft and keeping pilots rated through additional proficiency flights. The total cost at the enterprise level needs to be considered, in addition to any short-term cost savings of a particular flight test series using less capable and less expensive aircraft.

Scenario 2: Supersonic Transport Technology Research

A future LBFD is necessary if sonic boom mitigation work is to continue. Multiple sonic boom studies have been performed in the past. In 2011, the Waveforms and Sonic-boom Perception and Research (WSPR) study was performed. This test saw a number of partners work together. The WSPR effort utilized assets from NASA Langley Research Center, Wyle Laboratories, Gulfstream Aerospace Corp., Fidell Associates Inc., Pennsylvania State University, and Tetra Tech. The testing also benefited from the cooperation of Edwards AFB personnel (Creech, 2011). In 2012, the Farfield Investigation of No Boom Threshold (FaINT) testing was performed. Like the 2011 testing, partnerships were used to complete the testing (Creech, 2012). These tests utilized AFRC's fleet of F-15s, as pictured in Figure 5.2. The configuration of the F-15 allowed researchers to install experiments on the centerline testbed, which is not possible on the other AFRC supersonic aircraft.

The reference baseline, along with three partnering alternatives, can be found in Table 5.5. NASA is exploring flight research alternatives and partnering options for an LBFD effort. Extrapolating from past efforts, the baseline for this is a NASA supersonic aircraft testbed that, based on industry concepts, is highly modified to produce a low-boom demonstrator good enough to provide data for establishing regulatory limits. The alternatives explore partnering options with regard to the testbed but presume that NASA will provide support chase aircraft in all cases. Initially the LBFD would be flown in the confines of a test range but, given adequate confidence, could be flown in the NAS. The first alternative has NASA not partnering in order to maximize public benefit of a technology developed for minimizing sonic booms. Instead, NASA uses subscale UAS to make the demonstrator more affordable. The second alternative, on the other hand, involves expecting industry to provide the demonstrator; this would provide NASA with the data to make recommendations to the FAA on overland supersonic acoustic regulations, but technology developed would remain the property of the industry partner alone unless the partner was willing to share technologies and results more widely. Lastly, NASA could specifically strive to work with multiple partners to

Figure 5.2
NASA F-15 with Quiet Spike and Centerline Testbed Configurations

SOURCES: Thomas, 2006 (left); Tschida, 2013 (right).
RAND *RR1361-5.2*

maximize the public benefit through competition, but that is likely to demand additional resources to manage the increased scope.

While a UAS subscale demonstrator would do less to increase the TRL, it is likely adequate for establishing acoustic regulations. The unmanned nature of the test vehicle, combined with the restricted air space and range safety infrastructure available at DATR, would allow for greater risk-taking in the flight research. Alternatives vary on

Table 5.5
Scenario 2 Partnering Alternatives

Scenario	LBFD Reference Sources	LBFD UAS	Single Industry Partner	Competition
Technology	NASA and industry	NASA	NASA and industry	NASA, industry, and academia
Flight test aircraft	NASA and industry	NASA	Industry	Industry/academia
Flight test AC costs	$200 million to $600 million	$100 million to $300 million	$100 million to $300 million	$200 million to $600 million
Support aircraft	NASA supersonic	NASA supersonic	NASA supersonic	NASA supersonic
Support AC costs	$245,000 to $445,000	$245,000 to $445,000	$245,000 to $445,000	$353,000 to $632,000
Safety/range	AFRC/DATR	AFRC/DATR	AFRC/DATR	AFRC/DATR
Comments	X-plane test aircraft, with 3 fighter chase aircraft used.	Increased NASA cost; greater public intellectual property X-Plane demonstrator to be constructed by NASA	Decreased NASA cost and stricter IP limits. X-Plane demonstrator owned by industry	Increased NASA cost due to 50% more test flights and greater private partner competition. X-Plane demonstrator to be constructed by NASA and industry/ academia

SOURCES: NASA, 2012; NASA, 2016d; Office of the Undersecretary of Defense, 2013.
NOTES: Amounts converted to FY 2015 dollars. Assumes 10 sorties.

the flight test aircraft, but all are consistent on the type of chase and support aircraft necessary and the use of the DATR at AFRC. Each of the alternatives was rated in terms of safety, cost, time, and other considerations (such as partnering opportunities). The ratings are shown in Table 5.6.

Ultimately, the acquisition cost of a low-boom supersonic demonstrator, expected to be in the millions of dollars, outweighs the costs of support aircraft for a single series of flight tests. We thus conclude that the effort depends primarily on the resources that either NASA or partners commit to the development of overland supersonic technology and sonic boom shaping.

Scenario 3: UAS Autonomy Research

Planning documentation provided for this scenario is quite different than the others in that the effort is resource-capped but with a wide range of potential research directions. The UAS flight demonstration options are options for the FY 2016–2018 time frame and are scoped to be accomplished assuming a total cost of approximately $15 million. This plan calls for six different options:

- Option 1: UAS Congested Terminal and Airspace Evaluations
- Option 2: UAS Operational Environment Evaluations, IFR (Instrument Flight Rules) Conditions
- Option 3: UAS Operational Environment Evaluations, VFR (Visual Flight Rules) Conditions

Table 5.6
Scenario 2 Rating of Partnering Alternatives

Baseline	**Impact of Alternative Scenarios**		
Reference Scenario	**LBFD UAS**	**Single Industry Partner**	**Competition**
Cost to NASA: Near full-scale demonstrator acquisition and supersonic flight tests	Subscale UAS LBFD moderately reduces acquisition cost	LBFD acquisition cost sharing savings	Increased flight testing plus $150,000
Costs to Other Government: None	No significant change	No significant change	No significant change
Time: Driven by demonstrator acquisition	No significant change	No significant change	Potential increases due to added coordination
Safety: Modeling due to aerodynamic modification of manned aircraft	Can accept greater risk due to unmanned aircraft	No significant change	No significant change
Other: Limited partnering	Subscale aircraft may be less realistic sonic boom generator	Intellectual property rights access proportional to cost-sharing	Improved partnering across NASA, industry, and academia

NOTE: Green=substantially better; red=substantially worse.

- Option 4: On-Demand Emergency Response and Science Operations
- Option 5: Multiple UAS with Single Pilot Flight Evaluations
- Option 6: Civil Autonomous UAS Technology Development and Flight Demonstrations.

The baseline scenario is essentially the path of least resistance. Researchers simply leverage existing NASA research and capabilities while partnering with academics who can bring sensor or autonomy capabilities. As with other flight research, the UAS will require safety and photo chase support aircraft. Due to the speed and flight characteristics of the UAS, NASA chase aircraft will not need to be supersonic. The alternatives involve expanded partnering with either industry or other government entities and a contrasting simple alternative of going it alone. Table 5.7 shows the alternatives that were considered, with the ratings provided in Table 5.8.

The two expanded partnering alternatives have the advantage of increasing the amount of flight research given the set amount of NASA resources. However, in both cases NASA has to give up some control. The heavy partnering case saves government

Table 5.7
Scenario 3 Partnering Alternatives

Scenario	UAS Reference Sources	Heavy Partnering	NASA Technology–Focused	Governmentwide Partnering
Technology	NASA	NASA, industry, and academia	NASA	NASA and DoD
Flight test aircraft	NASA, academia, or lease	NASA, industry, and academia	NASA	DoD
Flight test AC costs	$10,000 to $216,000 or UAS acquisition cost	No UAS acquisition cost	$10,000 to $216,000 or UAS acquisition cost	$10,000 to $216,000 or UAS acquisition cost
Support aircraft	NASA	Academia	NASA	DoD
Support AC costs	$280,000 to $458,000	$90,000 to $180,000	$280,000 to $458,000 plus UAS acquisition or lease	$502,000 to $753,000
Safety/ range	NASA AFRC	FAA UAS ranges	FAA or NASA ranges	FAA, NASA, and DoD ranges
Comments	5 UAS and one B-200 are planned for this test.	Maximizes the variety of technologies/ algorithms tested with much less control over the development path. 1 aircraft and 1 UAS.	Maximize control over technology development path but with less efficient use of resources.	NASA and FAA bring technology and regulatory expertise matched to DoD UAS platform and interest in autonomous operations.

SOURCES: NASA, 2012; Office of the Undersecretary of Defense, 2013.

NOTES: Amounts converted to FY 2015 dollars. For flight test aircraft, assumes medium-size UAS costs between $10,200 and $36,400 and large UAS costs between $135,900 and $216,200 using USAF cost per flight hours for MQ-1B, MQ-9A, and RQ-4. Assumes 20–30 sorties.

Table 5.8
Scenario 3 Rating of Partnering Alternatives

Baseline	Impact of Alternative Scenarios		
Reference Scenario	Heavy Partnering	NASA Technology–Focused	Governmentwide Partnering
Cost to NASA: Defined at $15 million per year with selective partnering with government/industry	NASA costs constant or decreasing, but increased diversity of flight testing	Likely no change, but limited flight research as NASA bears most costs	Shares costs across NASA, DoD, and FAA with potential increases due to more-expensive DoD assets
Costs to Other Government: None	No significant change	No significant change	DoD provides significant cost sharing, but DoD costs are higher
Time: Three-year planned effort	Possible schedule delays, although UAS community is relatively agile	No significant change	No significant change
Safety: Consistent with FAA NAS requirements	Potential increased risk of test failures due to multiple safety standards	No significant change	No significant change
Other: Selective partnering	Significant partnering with industry and academia	Lack of partnering, but more flexibility to release intellectual property	Partnering with DoD and FAA

NOTE: Green=substantially better; red=substantially worse.

resources but reduces NASA's control over safety and probability of success, as they would operate on FAA guidelines. Governmentwide partnering would likely increase cost, but would share the increased cost across the government while allowing each government entity to bring their strengths to the table (e.g., NASA R&D, DoD operations, and FAA regulation).

Scenario 4: Evaluation of Alternative Biofuels

The fourth scenario studied is an evaluation of alternative fuels. This scenario was able to make use of several previous NASA projects, including the Alternative Aviation Fuel Experiment (AAFEX) in 2009, ACCESS in 2013, and ACCESS II in 2014 (NASA, 2014e). The scenario includes the partnering arrangement that was used for ACCESS, which used aircraft from other NASA centers as well as international partners. NASA Langley's HU-25C Guardian jet was used, as well as the Falcon 20-E5 jet owned by DLR, and a CT-133 jet provided by NRC-Canada. The aircraft used in ACCESS II can be seen in Figure 5.3.

The reference baseline is based directly on ACCESS II. Table 5.9 shows the alternatives to the reference baseline, with Table 5.10 showing the ratings.

Alternate scenarios use the same type of international partnering agreement as used in the reference scenario, though to different extents. Given the maturity of the

Figure 5.3
Partners in the ACCESS Tests

SOURCE: Tschida, 2014.
RAND *RR1361-5.3*

research area, the partnering options focus on conserving NASA resources by transferring flight research costs to other organizations without really changing them. In both the greater industry involvement and the DoD involvement alternatives, benefits outweighed costs. Costs either decreased or were transferred. However, DoD support

Table 5.9
Scenario 4 Partnering Alternatives

Scenario	ACCESS-II Reference Sources	Greater Industry Involvement	Involve DoD	Rely on International Partners
Technology	NASA	NASA and industry	NASA and DoD	NASA
Flight test aircraft	NASA	Industry	DoD	NASA
Flight test AC costs	$157,000 to $223,000	$157,000 to $223,000	$157,000 to $223,000	$157,000 to $223,000
Support aircraft	NASA, NRC-Canada, and DLR	NASA, NRC-Canada, and DLR	NASA, NRC-Canada, DLR, and DoD	JAXA, NRC-Canada, and DLR
Support AC costs	$236,000 to $593,000	$236,000 to $593,000	$236,000 to $593,000	$236,000 to $593,000
Safety/range	NASA	Industry	NASA	NASA
Comments	NASA DC-8 used as test aircraft. 1 fighter chase and 2 jet chase used.	Decrease NASA cost and involve industry partners	Decrease NASA cost and involve DoD partners	Would make use of partnerships around the world

SOURCES: NASA, 2012; Office of the Undersecretary of Defense, 2013.
NOTES: Amounts converted to FY 2015 dollars. Assumes 15–20 sorties. The flight test aircraft is a four-engine aircraft, for which acquisition costs vary widely.

Table 5.10
Scenario 4 Rating of Partnering Alternatives

Baseline	Impact of Alternative Scenarios		
Reference Scenario	**Greater Industry Involvement**	**Involve DoD**	**Rely on International Partners**
Cost to NASA: NASA provides alternative fuel aircraft; NASA, international partners provide chase planes with sensors	Decreased costs to government as partners provide both the aircraft using alternative fuels and the fuel	Transfer some costs from NASA to DoD for aircraft using alternative fuels	Eliminates flight research costs, NASA alternative fuel technology research continues
Costs to Other Government: None	No significant change	Transfer some costs from NASA to DoD for aircraft using alternative fuels	No significant change
Time: Six-month flight research series	No significant change	No significant change	Less ability to influence schedule
Safety: Four-engine aircraft to allow for two unmodified engines	No significant change	No significant change	May not meet U.S. military or civilian standards
Other: International partnering	Increased partnering with industry	Partnering with DoD and leveraging DoD fuel supply chain for alternative fuels	Limited NASA involvement

NOTE: Green=substantially better; red=substantially worse.

aircraft cost more to use than NASA's aircraft. Relying on international partners has the potential to lower costs through reliance on the partner nation to supply funding, but potential increases in schedule and safety risk have to be taken into account.

Conclusions about Partnering Alternatives

These flight research scenarios exploring alternative partnering arrangements are illustrative, but should be used with caution: No effort was made to optimize the proposed alternatives or identify optimal alternatives. Nonetheless, a number of insights are evident.

- The marginal cost of support or chase aircraft is relatively small (less than $1 million) for each flight research test series compared with either NASA spending on flight research capabilities (~$12–25 million annually) or ARMD's research budget (less than $500 million annually).
- The cost of flight demonstrators and research aircraft can reach hundreds of millions of dollars. While less-capable chase and support aircraft might produce savings on a cost-per-flight-hour basis for a flight research test series, the enterprise costs of acquiring and maintaining a greater diversity of support aircraft is likely even greater. Enterprise planning for flight research aircraft can only be optimized with reliable projections of future flight research.

- Partnering can transfer costs but not necessarily reduce them. Government partners are unlikely to provide flight research capabilities that are more cost-effective or more capable than those maintained by NASA. When costs are transferred to industry through partnering, there is certainly a benefit to the government and the taxpayer. However, industry partnering reduces NASA's control over the data, the technology, and the risks. Even when safety standards are maintained, the partnering can potentially affect schedule risk and probability of success.
- Decisionmakers must also take into account intangible benefits from partnering, such as developing and expanding the flight research community with the goal of leveraging future synergies in both technology development and regulatory issues.

Synergies Between Management Options

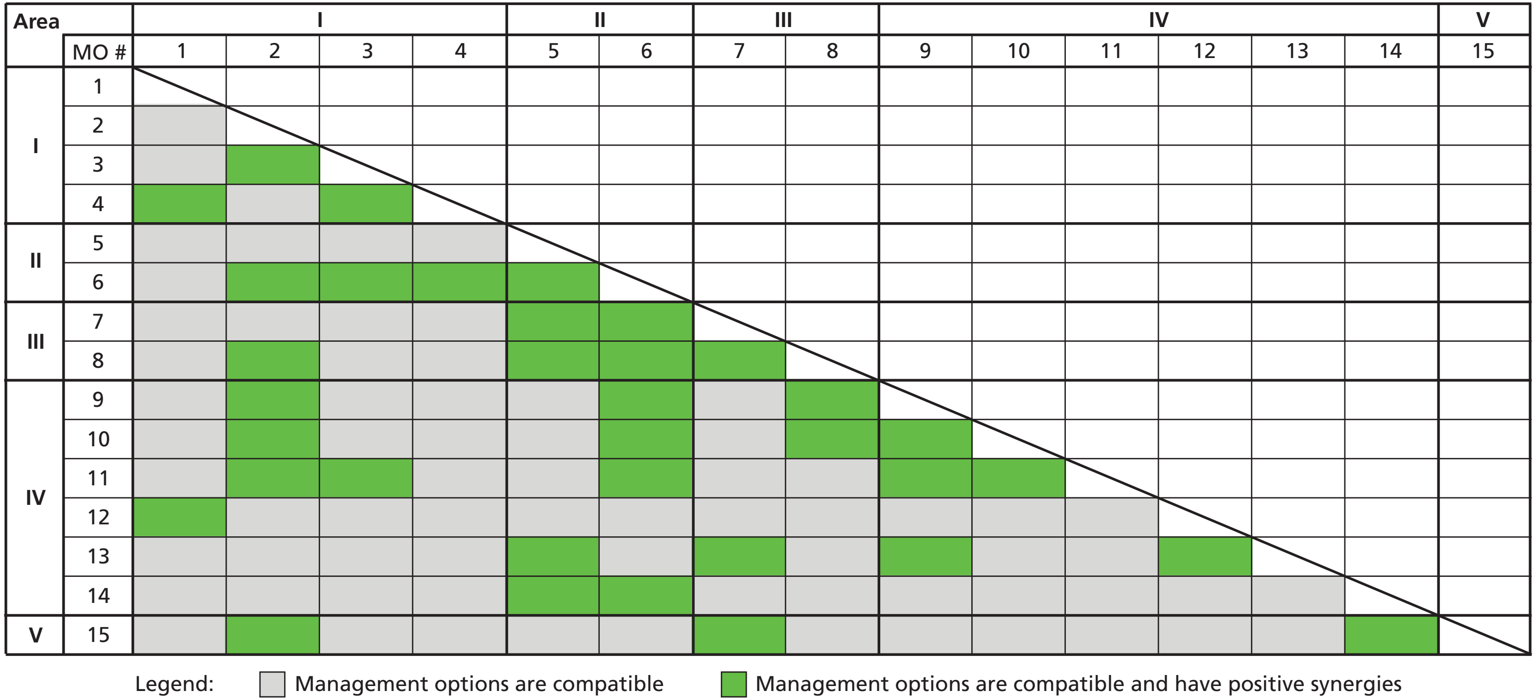
In addition to assessing each MO individually, we also looked at the compatibility and related potential synergies between pairs of MOs. None of the MOs were deemed incompatible with each other (meaning that implementing one would make implementing the other impossible), and there are positive synergies (i.e. mutually reinforcing benefits) among many of them, as highlighted in Figure 5.4. For example:

- Streamlining processes and reducing bureaucratic overhead (MO-13) also helps with attracting cooperation partners (MO-05) and implementing cross-center management (MO-09).
- Benefit analysis (MO-15) is closely linked to strategic investment (MO-02).
- Cross-center management of flight capabilities (MO-09) facilitates risk balancing (MO-10), implementation of strategic investment (MO-02), and increased partnering (MO-06).
- Improved access to flight test data (MO-14) can lead to more interest in cooperative research (MO-05) and partnerships (MO-06).

We find that relatively few potentially negative synergies exist:

- Fewer readily available flight research capabilities (which could result from implementing MO-02, MO-03, and MO-11) could mean less interest by outside organizations in collaborating with NASA (MO-05).
- Improving access to flight research data (MO-14) could lead to increased costs, because data access will have to be managed increasingly carefully as more-sensitive data are being generated—e.g., through increased military-related research (MO-02) or collaboration and partnering with commercial organizations (MO-05 and MO-06).

Figure 5.4
Compatibility Matrix for Management Options



NOTES: MO-01 = Planning integration; MO-02=Strategic investment; MO-03=Acquire-at-need; MO-04=Increase budget certainty; MO-05=Increase cooperation; MO-06=Increase partnering; MO-07=Space/military tie-in; MO-08=Annual needs survey; MO-09=Cross-center management; MO-10=Balance risks; MO-11=Adjust number of chase planes; MO-12=Voucher system; MO-13=Streamline process; MO-14=Improve data access; MO-15=ROI analysis.

RAND *RR1361-5.4*

- Expanded work in military and space-related research (MO-07) will likely increase the need for high-speed chase aircraft, which has to be taken into account when considering reducing the number of available aircraft (MO-11).

External Experts' Rating of Management Options

In addition to in-depth discussions about our approach and results, our interviews with senior external SMEs included gathering their quantitative assessments of individual MOs. Six SMEs chosen for their knowledge of flight testing and of aeronautics research were provided with a read-ahead package that included an overview of the project purpose, an early draft of the needs assessment, and a brief discussion of all MOs under consideration.[2] During subsequent phone interviews, they were asked to rate the relevance of each MO with respect to meeting ARMD's future flight research needs on a scale of 1 to 5, with 1 being "no relevance to meet future flight research needs" and 5 being "high relevance to meet future flight research needs." Figure 5.5 shows the distribution of the ratings provided by the SMEs. The vertical grey bars show median and quartiles, corrected for outliers; the solid black lines with labels show the average rating for each MO, and the dashed grey line indicates the overall average rating across all MOs.

Of the MOs reviewed by the SMEs, the following six received above-average ratings:

- increase research project budget planning certainty to two to five years (MO-04)
- perform annual survey of requirements, needs, and ideas (MO-08)
- explicitly balance and manage risks (MO-10)
- institute voucher system for simple exploratory flight research (MO-12)
- streamline the process that researchers must use to obtain flight research capabilities (MO-13)
- expand ROI analysis and promote results (MO-15).

The following MOs received the lowest scores, but were still ranked on the "relevant" side of the rating spectrum:

- encourage integration of flight research into project plans for appropriate research areas (MO-01)
- expand and highlight ties to space exploration and military applications (MO-07).

The remaining MOs (MO-02, MO-03, MO-05, MO-06, MO-09, MO-11, and MO-14) received moderately high ratings. Overall, the SMEs felt satisfied with the breadth of MOs considered.

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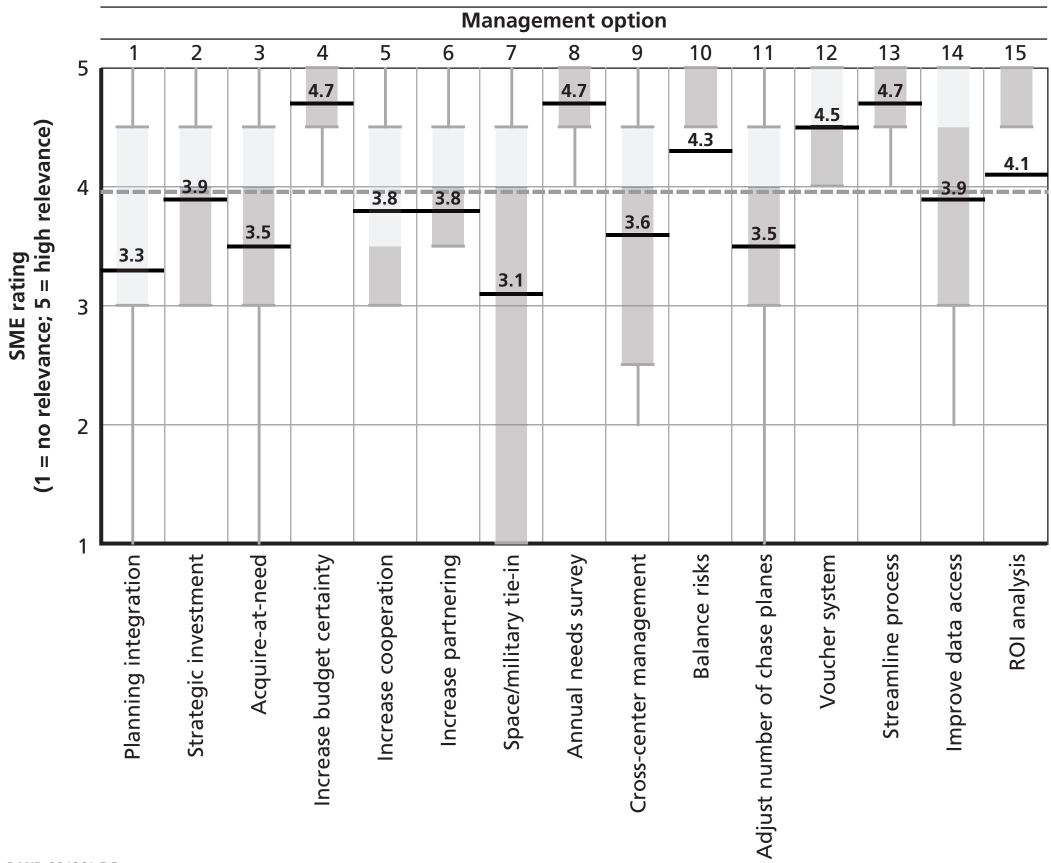
2 As already described, SME backgrounds varied, from a retired chief executive officer of a major aerospace company, to a former NASA center director, to a former test pilot. To foster candid discussion, SMEs were assured nonattribution and are thus not quoted by name.

Figure 5.5
SME Ratings of 15 Management Options, by Relevance



RAND *RR1361-5.5*

Summary

In summary, NASA Aeronautics has a wide range of MOs for increasing flight research and addressing related challenges. They fall into five general categories: Three work toward improving the supply side by enabling more flight research through increased funding and/or increased efficiencies; and two work toward improving the demand side by making flight research more attractive to researchers. Our assessment of the 15 options indicated that most appear to offer benefits that offset any disadvantages, or have disadvantages that can be moderated by careful implementation. There are no significant incompatibilities between the options. The external SMEs consulted for this project believed most of the options would be beneficial to ARMD's flight research mission.

CHAPTER SIX

Conclusions and Recommendations

ARMD asked RAND to estimate flight research capability needs over the next ten years (based on the ARMD SIP, which was released soon after our study began), map those needs against available capabilities, identify any gaps or excess, develop MOs for efficient management of those capabilities, and assess a key option—increased partnering—based on four typical flight research scenarios. A limiting factor for this effort was that NASA's annual program planning cycle, together with the newness of the SIP, did not allow us to obtain some specific flight research planning and needs documentation from ARMD programs, projects, and technical challenges. Moreover, while our effort was already scoped to exclude some potential aeronautics research areas (e.g., in support of defense and space exploration), the SIP by itself still outlines more research than even ARMD's increased budget can afford to address, leading to significant uncertainty in projecting ARMD needs over the next ten years. Thus, it was not possible to develop a detailed list or plan of needs at the level of utilization hours for specific aircraft, test ranges, and facilities over the next decade.

Nevertheless, the study team developed a high-level view of the types of capabilities needed for the flight research agenda outlined in the SIP, using information found in the flight research literature (e.g., Stoliker, 2005; Chambers, 2010; NRC, 2012; Pavlock, 2013; Merlin, 2013) and from interviews with NASA researchers and managers. We then performed a gap analysis by mapping these need categories against NASA's existing capabilities.

We found that NASA has capabilities in most areas where there is a specific need. Some gaps exist in testbed aircraft, but there has not been much active research recently in some of these areas (e.g., rotorcraft) and it is not clear that even ARMD's increased budget will enable it to re-enter these research areas in the foreseeable future. Moreover, such testbed aircraft can be acquired as needed. While acquiring testbed aircraft at the point of need requires lead time for modifications before research can begin, their commercial availability and uncertain use makes it hard to argue that it is strategically important to acquire them in advance. Instead, this argues for longer-range planning and partnering.

Insights gained from studying needs, capabilities, and gaps—as well as from identifying several additional issues affecting flight research at NASA—led us to develop 15

MOs that can help ARMD address the challenges it faces, such as the aforementioned planning problem (i.e., the divergence between funding certainty and associated time horizons for research, particularly given the ramp-up timelines for flight research capabilities). Subsequent qualitative assessment of these options by the research team and by external SMEs, plus a deeper analysis of the "increased partnering" option, identified their respective advantages and disadvantages. The SMEs provided additional ideas that helped us refine and prioritize the options, resulting in the following recommendations.

Recommendations

Based on our qualitative analysis and the inputs from our external SMEs, all 15 MOs described in Chapter Four seem appropriate, could have a positive effect on ARMD's flight research efforts, and are generally compatible with one another. Potential downsides are either outweighed by the associated benefits or can be moderated by careful implementation. Nevertheless, ARMD might not be able to implement such a large set of options. We have thus grouped and prioritized the MOs in the following way, which includes all options except MO-01 and MO-07, since those were rated less favorably by the senior SMEs (see Figure 5.5):

1. **Synchronize research planning and capabilities management.**
   – Focus flight research on a dynamic subset of ARMD's strategic thrusts that is determined by further analysis. To avoid spending resources on capabilities that will be unused or underutilized, ARMD should identify a subset of its SIP thrusts commensurate with an annual budget of approximately $800 million dollars and avoid investing in capabilities outside these affordable thrusts. To ensure the full SIP is covered eventually, focus areas could be rotated every few years. (MO-02, MO-04, MO-15)
   – Based on the resulting focus areas, consider divestment or reduction in readiness of flight research capabilities that are not currently needed. For example, the supersonic aircraft are one category of assets that could be mothballed or divested if no significant additional funds or partnering opportunities become available after the conclusion of the currently planned round of low-boom research. (MO-02, MO-03)
   – Implement longer-term, stable project and program planning out to five years, identifying a subset of projects and technical challenges that are guaranteed funding within high-confidence levels. Only invest in capabilities for the types of flight research domains for these projects and technical challenges. All other capabilities must be acquired when needed but only if sufficiently stable funding for both the research and capability acquisitions becomes available. (MO-04)

- Implement an annual online survey of research directions; consider using a process similar to the one implemented by NASA's Airborne Science Program, with a widely distributed announcement and information on the process and on points of contact for interested researchers (NASA, 2015f). (MO-08)

2. **Matrix-manage flight capabilities.**
   - Develop a matrixed management of flight assets across research centers to facilitate sharing of capabilities and looking for efficiencies while maintaining a local presence at each major aeronautics research center. This effort could be supported by value-chain analysis and should be synchronized with current "Capability Leadership" efforts at the agency level. (MO-09)
   - Streamline and simplify the process for researcher planning and use of flight research capabilities. Leverage the SMD's SOFRS to the degree possible (NASA, 2015e), and leverage local presence to help NASA researchers plan and execute flight research. Also facilitate access to domestic and foreign capabilities not available at NASA, including guidance on how to deal with intellectual property issues, in order to facilitate potential use. (MO-13)
   - Develop an online central repository of ARMD flight research test plans, data, results, and publications that is accessible to researchers based on a graduated system of access privileges. (MO-14)
3. **Trade agility for efficiency.**
   - Explore trading schedule and availability for reductions in infrastructure cost—for example, by acquiring at need or maintaining fewer backup chase aircraft. (MO-03, MO-10, MO-11)
   - Use partner capabilities to fill any gaps; e.g., partnering with Boeing for large commercial transport, partnering with the Army or foreign partners for rotorcraft testbeds. (MO-06)
4. **Subsidize exploratory flight research.**
   - Set aside a portion of the flight research hours (e.g., those available through the several hundred hours of proficiency flights per year) for short inserts of exploratory research through a voucher program for internal and external researchers. This will also leverage external research and may foster interest in additional collaboration. (MO-05, MO-12)
5. **Articulate benefits in monetary terms to facilitate ROI analysis and promote results.**
   - Continue efforts to demonstrate the results from aeronautics research, but add more quantitative estimates where possible, to help external stakeholders understand its potential value—for example, express fleetwide fuel savings due to more-efficient engines or better aerodynamics in dollars and tons of carbon dioxide saved. (MO-15)

In Closing

We have identified a number of viable options for ARMD (and NASA) management that could facilitate the desired increase in flight research and address related challenges. Implementing these MOs would help ARMD focus its efforts and improve efficiencies—both important for the prudent investment of government resources.

APPENDIX A

Further Considerations: Increase Partnering (MO-06)

Specific Partnering Opportunities with External Organizations

As for external flight research aircraft that could be leveraged through a partnership, our research identified a number of potential capabilities. Table 2.1 in Chapter Two provides a summary of key aircraft. However, partnering is not limited to utilizing a partner's aircraft; other capabilities can create opportunities as well (NRC-Canada, 2015).

Through selective partnering, NASA may be able to focus on investing in and sustaining a more limited number of organic capabilities. However, leveraging partners will require management, money, and technical proficiency to take advantage of capabilities that partners have to offer. As our research revealed, many potential partners have capabilities that may be of interest, but these may not cover the full span of NASA flight research needs, so this MO would have to be selectively employed to take advantage of specific capabilities present with potential partner organizations, and take into account some of the limitations of working with external organizations.

Table A.1 generally summarizes the five types of external organizations that NASA could consider partnering with, along with some benefits and limitations of working with each. Comparing some of the benefits illustrates that universities maintain diverse fleets of research aircraft in the slower-speed categories, including a growing number of unmanned or optionally manned systems (which also feature strongly among NASA's capabilities, however; see Table 2.1), whereas only U.S. government entities, such as the Air Force, support aircraft operating at the highest speeds. Commercial organizations can provide tailored, responsive research support within their respective envelopes of capability (or, in case of "nontraditional" commercial partners, insights from and access to new markets), whereas universities can offer opportunities to work with researchers who have experience designing experiments, publishing, and exploring new directions in flight research. Working with international organizations can offer opportunities to share in new technological developments overseas and contribute to U.S. public diplomacy efforts (Bress, 2013).

However, working with partners can also have limitations. There are restrictions on working with U.S. government partners like the Air Force, as well as with foreign entities. The former is driven by the high demand within DoD for capabilities and

Table A.1
Overview of Generic Partnering Opportunities

Partner Type	Example	Selected Unique Benefits	Potential Limitations
U.S. government	U.S. Air Force	Access to higher speed aircraft	Availability, technological sensitivities
"Traditional" commercial	Calspan	"On demand" support; a lot of experience supporting U.S. government research	Focus on support rather than on pushing the research envelope
"Nontraditional" commercial	Amazon	Injection of new ideas and concepts; access to broader markets	Different organizational and operational approaches
University	Mississippi State, University of Minnesota, Texas A&M	High caliber research staff, diverse selection of lower-speed aircraft and UAS	Variable access to and knowledge of federal safety certification, limited diversity in aircraft, sometimes independent research goals
International	DLR German Aerospace Center	Access to overseas technology, diplomatic benefits	Regulatory restrictions, sometimes independent research goals

information sensitivity. The latter relates to regulations on technology-sharing and differences in safety and other procedures between countries. Universities may differ in their approaches to and experience with safety certification processes. Partners may also have independent research agendas to pursue, and commercial organizations may be more focused on technologies approaching market readiness than on lower-TRL research. Organizational cultures also may differ—including approaches to such critical issues as safety of flight and intellectual property protection.

Here, we discuss some specific organizations that NASA has partnered with (in some cases), and could continue to do so. One example of a commercial organization that could prove valuable for partnering is Calspan, which offers access to aircraft, personnel, and facilities along with the added benefit of a flight research process that has been refined over several decades. Calspan has two research arms, the Flight Research Group and the Transonic Wind Tunnel Group, and is known for stability and control research. Recently, it has supported a significant amount of UAS research using their Learjets, including automated aerial refueling efforts and sense-and-avoid testing. It has a number of aircraft available for research, including four Learjet "in flight simulators" that can be modified with programmable flight systems, as well as a Gulfstream G-3. It also maintains an F-16 VISTA and a SAAB 340 for the Air Force and Navy test pilot schools, respectively.[1] Calspan uses the airspace over Lake Ontario for testing. It has about 50 staff, including ten former military test pilots with backgrounds in engineering who have retired from the Air Force and Navy. It employs aerospace, mechanical, and computer engineers (among others), as well as mechanics with expertise in sheet metal, paint, and other materials and processes need to make modifications and maintain aircraft. Calspan

[1] Note that any NASA requests to utilize these aircraft would have to go through the USAF.

works closely with the FAA, Air Force, Navy, and NASA for flight safety certification. NASA also has a history of collaboration with U.S. aeronautics manufacturers, including recent research using Boeing's EcoDemonstrator, the collaboration with Gulfstream on Quiet Spike low-boom technology, and the High Ice Water Content flight campaigns involving multiple NASA centers, Boeing, and Rockwell-Collins.

Several universities maintain some level of flight research capability, including the University of Minnesota, which currently has available five research aircraft operating at low subsonic speeds, as well as three test pilots and ten researchers and engineers. The university has an FAA COA (certificate of authorization) for its airspace and is restricted to daytime, "visual flight rules" flight operations at 400 feet above ground level or lower. Some recent projects include research under a grant from the Department of Homeland Security into the use of cell phone signals to address GPS-denied navigation, as well as research under a grant from the state of Minnesota to explore improvements for unmanned aircraft and sensors for agriculture, and research into improving reliability for unmanned aircraft using data- and model-based techniques for detecting faults and reconfiguring the aircraft to continue flying safely. Finally, university researchers are working on a NASA Research Announcement (NRA) to develop lightweight, high–aspect ratio aircraft with wings that can morph their shape to optimize efficiency for the current flight condition. They are looking to expand their research into GPS-denied navigation, improving aircraft and small UAS reliability, and improving commercial aircraft efficiency. It takes one to three months to staff up and begin working on a project at full levels. This varies depending on demands placed on staff and the time of the year. The university employs a flight approval process with an early review stage (similar to a PDR [preliminary design review]) and a test readiness review stage, which includes a risk and hazard analysis.

Finally, we interviewed some flight research organizations outside of the United States that expressed interest in partnering with NASA on research of mutual concern. One example is DLR, the German Aerospace Center, which is a nonprofit organization that is semiautonomous but closely aligned with the German government and its R&D strategies, since most of their funding is provided by the German federal government and several German state governments (mostly those that have DLR locations). DLR has most of its manned aircraft used for aeronautics research at its Braunschweig location; aircraft mostly used for science flights are in Ottobrunn near Munich (see Table 2.1). DLR has more than ten research pilots, all of them graduates of a test pilot school, all with engineering or science degrees, and all with extensive glider plane experience (which provides improved stick-and-rudder and energy management skills). Some of the pilots fly part-time for commercial airlines (or fly helicopters for Germany's civilian search-and-rescue organization) to help with proficiency time. DLR had a good experience collaborating with NASA for the ACCESS-II campaign, and appears interested in expanding the collaboration. The ACCESS-II campaign included aircraft and resources from AFRC, LaRC, DLR, and NRC-Canada. It serves as an example of multiple organizations contributing resources and working together to investigate a research problem.

Limitations and Practical Considerations of Partnering

Existing statutes and regulations give NASA extensive authority to pursue partnerships on terms it deems appropriate. While some NASA staff we interviewed made general references to "problems" or "obstacles" in law or policy that limited their ability to partner and use Space Act or cooperative agreements, we found—and NASA attorneys confirmed—that there are no substantive roadblocks for partnerships. If anything, some staff may benefit from assistance in considering and managing partnerships.

NASA's authority in these matters stems from the National Aeronautics and Space Act (Public Law 85-568, 1958), which has been amended several times since passage. Like all federal agencies, NASA is permitted to contract for services through open, competitive procurement procedures, which are used for some activities associated with flight research (e.g., airplane maintenance). In addition, NASA has special authority to engage in nonstandard contracts and agreements based on 51 U.S.C Sec. 20113(e), a provision of the Space Act, which reads (emphasis added):

> (e) Contracts, Leases, and Agreements. In the performance of its functions, the Administration is authorized, without regard to subsections (a) and (b) of section 3324 of title 31, to enter into and perform such contracts, leases, *cooperative agreements, or other transactions* as may be necessary in the conduct of its work and on such terms as it may deem appropriate, with any agency or instrumentality of the United States, or with any State, territory, or possession, or with any political subdivision thereof, or with any person, firm, association, corporation, or educational institution.

NASA has institutionalized this authority in a broad category it calls Space Act agreements, which include "Reimbursable, Nonreimbursable, and Funded Agreements," (NASA, 2008) and CRADAs (NASA, 2013a), sometimes referred to simply as cooperative agreements. Reimbursable agreements are used when NASA offers its facilities and services to outside entities and is subsequently reimbursed. Nonreimbursable agreements, sometimes referred to as partnering agreements or cost-sharing agreements, involve NASA and an outside entity engaging in "mutually beneficial activity that furthers the Agency's missions, wherein each party bears the cost of its participation, and there is no exchange of funds between the parties" (NASA, 2008). Work with foreign entities is conducted through international agreements under this same policy.

These varied agreements can be used in flight research to engage either private-sector or foreign entities when standard commercial contracting is not viable or does not serve NASA's and the public's interests. While there are no legal limits on the number, size, and type of Space Act agreements, NASA's attorneys review all such agreements to ensure the work being performed is in keeping with NASA's mission and cannot reasonably be achieved through competitive commercial contracting. The AFRC's Office of the Chief Counsel stated that while smaller agreements are reviewed at the center level, current NASA policy requires NASA HQ's Office of the General Counsel (OGC) to review any Space Act agreements valued at over $1 million.

On multiple occasions during the course of this research, NASA staff members made general references to "problems" or "obstacles" in law or policy that limited their ability to partner and use Space Act or cooperative agreements. However, NASA staff did not provide specific examples of agreements that failed because of legal or policy restrictions. AFRC and OGC attorneys also were unable to provide examples of partnering agreements that were unsuccessful due to legal restrictions. Rather, they indicated they work regularly with NASA staff to craft agreements to aid them in meeting their research needs and goals. Most notably, in interviews with both AFRC and NASA HQ OGC attorneys, they stated unequivocally that no proposed agreements had been unsuccessful due to an inability to negotiate intellectual property terms.

Nevertheless, this topic may have to be explored further to expand partnering between ARMD and external—particularly commercial—organizations. In informal conversations with members of the research team, several industry representatives voiced concerns about partnering with NASA, in part due to intellectual property concerns, but going beyond anecdotal observations would require an extensive, anonymous industry survey.

Regarding ground infrastructure, NASA has reliance agreements with air bases and airports near its flight research centers. Also, AFRC is a tenant inside Edwards AFB, and NASA maintains a noncontractual relationship with Edwards for access to the runway and airspace, as well as some basic services, such as utilities and fire protection. This relationship is captured in a series of Memoranda of Agreement (MOAs) and Understanding (MOUs); additionally, an "Alliance Council" is in place to institutionalize the working relationships (NASA, 2014i).

Partnering with industry on flight demonstrators can increase the amount and types of flight research possible. This can fill gaps in NASA's capabilities, such as for rotary wing research or research requiring large transport aircraft. It can also help demonstrate downstream customers' level of interest in ARMD research and facilitate technology transfer. Precedents include ARMD collaboration with Boeing on the EcoDemonstrator and the X-48B vehicle, as well as ARC rotorcraft research using Army helicopters.

While academia may not be able to offer research aircraft, it can provide other research services, such as instrumentation or CFD support. For example, the Texas A&M Flight Research Laboratory has equipment to conduct hot-wire and hot-film anemometry, infrared thermography, and other flight test instruments. Mississippi State University supports research in CFD in addition to aerodynamics, structures and composites, structural reliability, and fatigue and fracture, among other areas of engineering. Academia could also contribute unmanned subscale vehicles.

As an international example, DLR and Airbus have a partnership arrangement for use of DLR's Airbus A320 (D-ATRA) testbed aircraft. Under the agreement, Airbus is testing the concept for a fuel cell that, in theory, would replace the aircraft's auxiliary power unit (DLR, 2012). The partnership works because DLR operates a production aircraft in a test configuration, which allows the manufacturer (Airbus) to test new and innovative equipment onboard a fully operational commercial aircraft.

One specific type of partnership worth discussing involves a long-term strategic relationship wherein NASA provides guaranteed financial or other support for external capabilities to help ensure the availability of those capabilities. Examples for such long-term support commitments include the Boeing Corporation's series of five-year contracts providing long-term support of the QinetiQ five-meter pressurized wind tunnel in the UK (QinetiQ, 2013b), and the 25-year Long-Term Partnering Agreement between the MOD and QinetiQ Group running from 2003 to 2028. Under the latter agreement, which is somewhat akin to a GOCO relationship in the United States, QinetiQ manages, maintains, and invests in the T&E capabilities on 17 MOD-owned installations to "ensure that the capability is maintained and developed to meet the MOD's evolving needs" (QinetiQ, 2013a). Although these examples involve organizations outside NASA, they illustrate the range of possibilities and can provide case studies from which to draw lessons learned.

However, since individual research projects, by necessity, mainly have short-term needs and priorities, they cannot be expected to fund such strategic capabilities by themselves. Thus, if NASA relies on outside organizations to provide such strategic capabilities, then it might become necessary to set aside strategic funds for capabilities beyond what is required by short-term project needs in order to keep those capabilities available. This is similar to the "infrastructure" subsidies for some of NASA's internal capabilities. Deciding which external capabilities might warrant such stewardship (and at what level), given their value to NASA, requires additional thorough analysis of strategic considerations, research priorities, and cost factors.

APPENDIX B

Further Considerations: Cross-Center Management (MO-09)

The structure of a matrixed organization to manage NASA's flight research capabilities requires further consideration, but a straightforward approach could simply integrate the centers' flight research management offices so that reporting, meetings, and coordination cross center boundaries. Given the critical importance of support from each research center, the initial structure may best be served by such an approach, so that center ownership and investment remains. For example, while assets are ultimately owned by NASA at the agency level, the research centers currently control the assets in practice. A matrix management structure would result in an entity at each center that serves the local center and indirectly reports to the local center director on issues such as safety and service, but functions as part of a coordinated whole that really serves all NASA researchers. In other words, it is a new service function whose customers are the local centers, local researchers, and NASA as a whole. Financial support mechanisms would have to be worked out. Ideally, from the perspective of center directors, they would lose some direct personnel authority but gain improved and more-efficient support for their local researchers, while still maintaining oversight of key functions (e.g., safety certifications) and gaining larger coordinated responsibility for the entire matrixed organization. Such shifts in authority, responsibility, and benefits is why the exact structure of the resulting organization would require further analysis and negotiation among the stakeholders to address concerns, statutory and regulatory responsibilities, rewards, and incentives.

Planning, supervision, leadership, and personnel functions under a matrixed organization could be performed by an integrated flight operations management team, utilizing management expertise at all centers and coordinating their activities. This would facilitate regular meetings across centers to share knowledge of all NASA capabilities, coordinate utilization and planning, balance workloads, further share expertise beyond current efforts, and facilitate sharing of both personnel and capabilities such as aircraft. Personnel evaluations would be written by the unified cross-center management organization and would be contingent on providing the best services regardless of location. Performance inputs from "line" research and center units would provide customer-service evaluations and ensure that local needs are still met. We note that NASA's recent decision to assign additional aircraft-related responsibilities to the AMD is an additional step in the direction of better coordination across flight operation organizations, as is the implementation of the NASA Aircraft Management Information System.[1] However, due to the specific needs of flight research, a manager/advocate dedicated to flight research also might be beneficial.

While the matrix management structure would need to be reviewed and approved by NASA leadership (e.g., through the Inter-Center Aircraft Operations Panel, which meets semiannually), it would provide closer integration and more-frequent interactions on top of those offered by the panel. Consideration would also have to be given to ensuring continuation of critical functions such as safety, for which center directors currently have the ultimate responsibility at their center. Finally, implementation would need to give attention to cultural factors in building a shared vision and purpose (see, for example, Bartlett and Ghoshal, 1990). This illustrates why further work is needed to reach agreements on the exact structure and practical arrangements for the matrixed organization.

Integration, Not Competition

Using basic market and management principles, we suggest that continuing on the path of improved integration (e.g., through a matrixed organization) is better than moving in the opposite direction of increasing competition between flight operations organizations at the different research centers as a way to drive efficiency. In a commercial free market, the presence of more competitors is generally believed to yield "better" outcomes (e.g., lower cost, higher quality). However, each competitor has fixed costs that it must cover in its price to remain in business. More competitors thus means higher total fixed costs that have to be spread out over the customer base, especially in areas such as flight research, where fixed costs are high to begin with (see Figure 3.1). In addition, competition in a free market is not the same as competition within a large, complex government organization: Property rights are assigned, prices are set in fundamentally different ways, and government and privately owned organizations pursue fundamentally different goals. However, over the long term, all costs become variable, suggesting that competition among offices should become more cost-effective as the decision horizon increases.[2]

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[1] Sufficient future funding for the information system seems to be uncertain (NASA, 2015c, p. 48).

[2] In practice, we observe that even as DoD has centralized its industrial activities into "centers of excellence" that have limited real-time competition among offices, centers have continued to compete for new workloads. As DoD has added new weapons to the force, centers have competed to support the weapons. As DoD has added new support workloads to extend the lives of weapon systems or modify weapon systems, centers have competed for this workload. And, at the margin, they have competed for workloads with private companies. This competition, of course, has been as heavily colored by politics as it has been by pure economic considerations. The same would likely be true at NASA.

Full Consolidation Is Probably Not Practical

On the other hand, consolidating all flight research activities at a single NASA center would have to overcome political obstacles.[3] In practice,[4] this would likely reduce the responsiveness of flight research operations for researchers at the other centers. Also, loss of local capabilities would introduce inefficiencies for researchers by forcing them to conduct all flight testing at a distant center.

Recent findings from the area of organizational science further illuminate this issue. Large, complex organizations inevitably face the challenge of coordinating line activities (comparable to NASA's mission directorates) with their functional activities, which (like NASA's mission support directorate and, to a lesser extent, its centers) provide common, organization-wide services to individual line activities. Recent trends in best commercial practice have seen a growing emphasis on integrating "vertical" end-to-end value chains within line activities and opening "horizontal" coordination and communication among functional activities through the use of long-standing cross-functional teams.[5] Value chains identify the final products of an organization, then identify metrics and incentives that each line entity can use to align activities for an individual link within the greater value chain to improvement of these final products. "Improvement" involves achieving better matches among the attributes of the final products and what their users want in terms of cost, reliability, and other performance characteristics—what the quality and Lean Six Sigma communities have come to call "value added."

As organizations get to understand their value chains better, they tend to reorganize themselves around them and reduce the number of boundaries within an organization that these value chains must cross. But where value chains must cross organizational boundaries—or even pass outside an organization to external suppliers—organizations set up long-term relationships to identify common goals and

[3] For example, Congress at one point prohibited transfer of research aircraft to a consolidated center (Public Law 104-204, Section 431, 1996).

[4] The appropriate degree of centralization depends on how an organization manages itself internally, which is an empirical matter that tends to change slowly but repeatedly over time in response to organizational learning. That learning occurs in a state of bounded rationality that inevitably leads decisionmakers to choose organizational structures that are "good enough" and never truly optimal in any objective sense. Competition among organizations tends to discipline this learning process. Private organizations that make bad decisions fail to survive. Such risk of failure, of course, does not discipline government organizations.

[5] These trends were first documented for a broad audience in Womack, Jones, and Roos (1991). The Toyota Production System came to embody these trends; a classic description is available in Ohno (1998). These trends were initially observed in manufacturing activities, but have since spread, through total quality management and its successor, Lean Six Sigma, to a broad variety of service activities. For discussions of how these trends relate to a variety of federal government activities, see Camm et al. (2001), Moore et al. (2002), and Camm (2002; 2003).

monitor mutual efforts to achieve those goals.[6] Cross-functional teams play an important role in maintaining such relationships. Organizations have increasingly delegated responsibility to these teams and structured incentives around their performance as teams, rather than around the performance of individual team members, who by definition report through separate chains of command within the organization as a whole. And when value chains link separate companies, best practice has given increased attention to long-term coordination among the very best partners available. Competition disciplines this coordination, giving a buyer or seller the option of seeking a better partner if the partnership does not perform as expected. But when partnerships are in place, efforts to increase competition can actually degrade coordination and induce partners to withhold information and sacrifice long-term mutual gains for short-term opportunistic behavior.

Within organizations, efforts to coordinate specific activities often take the form of assigning decision rights in two ways: one is relatively simple, one is more complex. In the simpler form, such assignment of decision rights is more likely to give an office within an organization responsibility for a decision (1) the more closely the goals of that office align with the goals of the organization as a whole, (2) the more "latent information"—information that cannot easily be shared between offices within an organization—that office has that is relevant to the decision, and (3) the better the office's analytic capability is to use the information it has to promote its own goals.[7] In a more sophisticated and realistic form, the assignment of decision rights in complex organizations recognizes that many offices often have useful insights and capabilities relevant to any one decision. As a result, decision processes sequence decisions. A sequence starts by giving higher-level offices more control over general allocation of resources, then gives lower-level offices progressively more and more control over specific resources allocated to them for their use.

Also, many decisions occur in cross-functional teams that bring together several offices to balance their goals and apply the information and analytic capabilities that they control. When many cross-functional teams are in place, the goals of the organization as a whole can, in effect, emerge from these teams and evolve as these

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6 Such outsourcing has proven to add value to value chains when it allows organizations with relevant, complementary core competencies for different links in the value chain to align their activities to common goals. Such alignment has been feasible precisely because organizations have learned to create and sustain long-term relationships with one another. Such relationships change how competition occurs in the markets where buyers and sellers deal with one another.

7 This framework was first proposed in Jensen and Meckling (1992; also published in the *Journal of Applied Corporate Finance*, Fall 1995). A growing empirical literature has since tested the framework and found strong empirical evidence that it helps explain the internal organization of successful commercial firms. For a more general discussion of this framework and other materials relevant to it, see Jensen and Wruck (1998).

teams react to changes in the environment of the organization as a whole.[8] Thus, cross-functional teams could be a less drastic way to try integrating capabilities across the research centers. However, they involve duplicative participation from each center's operation group rather than having a single local contact that can represent and reach out to other centers' capabilities. If NASA chose to pursue this MO, then different options for how the matrixed organization would function would have to be considered, including whether cross-functional team meetings could serve as a coordinating and information-sharing body.

8 For more information on how goals can emerge and evolve in this way, see March (1994), which documents the lectures from a Stanford University Graduate School of Business course.

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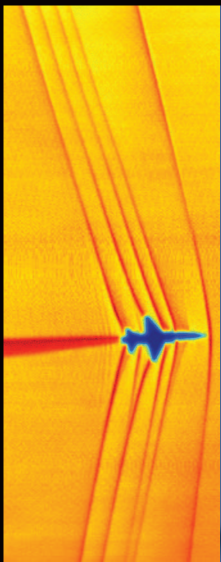

NASA's Aeronautics Research Mission Directorate (ARMD) is working to expand flight research in order to advance the maturation and demonstrate the application of new aeronautics concepts and technologies over the next ten years. It asked RAND to assess available flight research capabilities and future needs, identify any gaps or excess infrastructure, and develop management options that would facilitate increased and improved flight research. We found that NASA has strong flight research capabilities in most areas relevant for flight research. The few gaps that we identified could be filled through partnering or acquisition of vehicles from the marketplace when needed. Other gaps exist in sub- and full-scale experimental aircraft, but these cannot be acquired before the specific research projects are planned and funded. ARMD is already pursuing multiple efforts to increase flight research. We recommend that ARMD continue its efforts to enhance long-range planning and project funding certainty so that researchers can better include flight research in their plans and specific infrastructure needs can be identified further in advance. Cost-sharing through partnerships remains a valuable option, although industry positioning for increased intellectual property rights may be a limiting factor. Stewardship of flight research capabilities can be improved by instituting a unified, matrixed management structure across centers that can help align incentives while centralizing and improving utilization, partnering, and external outreach efforts. Finally, access and sharing barriers for researchers can be lowered through a voucher system for simple flight research efforts, streamlined processes for planning and access, and instituting state-of-the-art knowledge management approaches to store flight research data and share it with the aeronautics community.

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