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DOCUMENTED BRIEFING

An Update of the Nation's Long-Term Strategic Needs for NASA's Aeronautics Test Facilities

Philip S. Antón • Raj Raman • Jan Osburg • James G. Kallimani



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Prepared for the National Aeronautics and Space Administration and
the Office of Science and Technology Policy



INFRASTRUCTURE, SAFETY, AND ENVIRONMENT and
NATIONAL SECURITY RESEARCH DIVISION

The research in this briefing was funded and sponsored by NASA Headquarters and the Office of Science and Technology Policy. The study was conducted jointly under the auspices of the RAND Transportation, Space, and Technology (TST) Program within RAND Infrastructure, Safety, and Environment (ISE); and the Acquisition and Technology Policy Center of the RAND National Security Research Division (NSRD).

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Preface

The National Aeronautics and Space Administration's (NASA's) major wind tunnel (WT), propulsion test (PT), and simulation facilities exist to serve NASA's and the nation's aeronautics needs. RAND Corporation researchers conducted a prior study of these facilities from 2002 to 2003, identifying (1) NASA's continuing ability to serve national needs, (2) which facilities appear strategically important from an engineering perspective given the vehicle classes the nation investigates and produces, and (3) management challenges and issues (Antón et al., 2004a, 2004b).

This documented briefing (DB) is the final report from a new, one-year study (conducted from September 2006 through January 2008), partially updating the prior assessment. The study focuses on updating the list of facilities in the prior study that were deemed to be *strategically important* (again, from an engineering perspective) in serving those needs. This update also adds a new assessment of national needs for six major aeronautics simulators at NASA and lists those deemed strategically important.

This DB should be of interest to NASA, the Office of Science and Technology Policy, the Department of Defense, the Office of Management and Budget, congressional decisionmakers, and the aerospace industry.

The research in this briefing was funded by NASA Headquarters and jointly sponsored by the Office of Science and Technology Policy. The study was conducted jointly under the auspices of the RAND Transportation, Space, and Technology (RAND TST) Program within RAND Infrastructure, Safety, and Environment (ISE); and the Acquisition and Technology Policy Center of the RAND National Security Research Division (NSRD).

Questions or comments about this briefing should be sent to the project leader, Philip Antón (anton@rand.org).

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Martin Wachs, Director
Transportation, Safety, and Technology Program, ISE
RAND Corporation
1776 Main Street
P.O. Box 2138
Santa Monica, CA 90401-2138
310-393-0411, x7720
Martin_Wachs@rand.org

The RAND Acquisition and Technology Policy Center

This research was jointly conducted within the Acquisition and Technology Policy Center (ATPC) of NSRD. NSRD conducts research and analysis for the Office of the Secretary of Defense, the Joint Staff, the Unified Combatant Commands, the defense agencies, the Department of the Navy, the Marine Corps, the U.S. Coast Guard, the U.S. Intelligence Community, allied foreign governments, and foundations.

For more information on RAND's Acquisition and Technology Policy Center, contact the Director, Philip Antón. He can be reached by email at atpc-director@rand.org; by phone at 310-393-0411, extension 7798; or by mail at the RAND Corporation, 1776 Main Street, Santa Monica, CA 90407-2138. More information about RAND is available at www.rand.org.

Contents

Preface	iii
Summary	vii
Acknowledgments	xiii
Abbreviations	xv
 CHAPTER ONE	
Background	1
 CHAPTER TWO	
Wind Tunnels and Propulsion Test Facilities	21
 CHAPTER THREE	
Simulators	51
 CHAPTER FOUR	
Conclusions and Recommendations	63
WT/PT Facilities	65
Simulation Facilities	65
 APPENDIXES	
A. NASA, DoD, and Industry Input Details	69
B. Simulator Descriptions	75
C. Technical Discussion of Simulation and Simulators	81
 References	 97

Summary

Introduction

The National Aeronautics and Space Administration (NASA) asked RAND to partially update its prior study of NASA's major wind tunnel (WT) and propulsion test (PT) facilities (Antón et al., 2004a, 2004b) to see whether any changes have occurred in the strategic need for these capabilities and to expand the original assessment to include major simulators.

The objectives of this study are to update our prior list of NASA WT/PT facilities and to create a new list of NASA simulation facilities that are strategically important in serving national needs of NASA, the Department of Defense, and U.S. industry. *Strategically important* facilities are those that offer significant and cost-effective technical capabilities important for the long-term research, development, testing, evaluation, or sustainment of the range of the kinds of aeronautic vehicles that the country develops and uses. Here, *strategic* implies a consideration of needs independent of the ups and downs of immediate or budgeted program funding and focuses instead on the classes of vehicles that the country pursues.

We measured and derived national strategic need and importance from an engineering perspective, asking design engineers and users to explain their long-term strategic testing needs as determined by the types of aeronautic vehicles on which they work generally. Their consideration would include not only currently budgeted vehicle projects but future vehicle classes that might be produced to serve national interests. If the nation made an overt, long-term strategic decision to no longer produce a certain vehicle class, then we would be able to eliminate the test facilities needed only for production and sustainment of that class of vehicles. For example, the United Kingdom (UK) Ministry of Defence (MOD) decided about a decade ago to no longer develop complete fixed-wing aircraft and to instead acquire them from other countries; the UK then no longer needed the WTs needed to produce such vehicles.

This discussion with design experts explored not only the technical capabilities they need and use but other factors that affect their decisions to use specific facilities, including cost, availability, and workforce quality. These additional factors provided insights into how to determine the importance of a strategic need and how NASA's capabilities serve that need relative to any competing test capabilities elsewhere. Strategically important needs were those that serve existing NASA programs and their long-term plans, Department of Defense (DoD) needs critical to meeting the DoD's mission, or other DoD and industry needs. Our analysis judged the needs either by their strength in a single sector or by their breadth across multiple sectors.

Our analytic method does *not* rely on an explicit, detailed, and exhaustive long-term national strategy plan for aeronautics test capabilities. This is because such a plan still does not exist and because this study is intended to help inform the creation of such a plan. Also,

aeronautics test facilities and operations are only partially funded by specific line items in the NASA budget. Thus, the study's determination of facility needs and our resulting conclusions and recommendations are not based on the federal budget process as a direct indicator of policy dictates of facility needs. As with a national plan, this study is intended to help inform that process rather than be driven by it.

To identify any changes in national WT/PT needs since our last study, we resurveyed the same DoD service and industry respondents using the same questions to understand their long-term strategic needs (see Antón et al., 2004b, pp. 120–129). To identify specific differences, respondents were sent their own prior survey responses and were asked to identify any changes since 2003.

We also employed the recent DoD study of “critical” facilities conducted by the Defense Test Resource Management Center (DTRMC) (see AT&L, 2007), including a detailed look at the unpublished information collected for that study on facilities that may be strategically important or beneficial but not deemed critical.

In addition, we solicited information on strategic needs from the current NASA research programs (aeronautics and space) and reviewed their program plans.

To assess simulator needs and capabilities, we reviewed the simulator types and their general use and asked NASA, DoD, and industry users to describe their strategic uses for these capabilities.

Finally, although the study focused on national needs and NASA's aeronautics test infrastructure, national needs are not dictated or met solely by NASA's test infrastructure; DoD, U.S. industry, and foreign capabilities also serve many national needs. However, our study was not chartered or resourced to examine data sets for these alternative facilities to fully understand consolidation opportunities between NASA and non-NASA WT infrastructures. Nonetheless, our findings revealed no evidence to change our prior recommendation that such a broader study is important and warranted.

Observations Based on an Updated Assessment of WT/PT Facilities and a New Assessment of Simulators

Update of Assessment of WT/PT Facilities

Overall, our updated assessment finds that NASA's aeronautics test facility capabilities remain strategically important for serving the national strategic needs of the aeronautics research, defense, commercial, and space communities.

We expect utilization to continue to vary from year to year and from facility to facility, causing important management challenges. This reflects the ups and downs of research, development, test, and evaluation (RDT&E) programs and the historical reduction in the frequency (but not elimination) of programs across the range of aeronautic vehicles. This variation in use implies that NASA management will need to take a diligent, long-term, strategic view to preserving strategically important capabilities. As we recommended in our prior study (Antón et al., 2004a), this view will require shared financial support to keep facility prices stable, competitive, and commensurate with individual testing value. NASA should continue to provide this strategic management and shared support (e.g., as it is currently doing through the NASA Aeronautics Test Program [ATP]).

The U.S. need for WT/PT facilities has not changed significantly since our prior study. However, the realities of ongoing low use at certain facilities have logically driven some NASA management actions.

WT/PT Facilities

There were 31 NASA WT/PT facilities during our prior study that met the study criteria, although NASA had already closed an additional 13 other facilities since the early 1990s. Of these 31, twenty-nine facilities were rated as strategically important in our prior study. Twenty-seven remain so, but two should be removed from that list. The two other facilities that were identified as *not* strategically important in our prior study remain so.

The formerly weak strategic support from the user community for the Langley Low-Turbulence Pressure Tunnel (LTPT) has declined even further, and there are no current NASA program needs for it. Boeing (the only prior industrial advocate) suggested that NASA invest in new capabilities at an alternative facility, such as the Langley National Transonic Facility (NTF), to provide two-dimensional testing capability similar to that offered by the LTPT. Since significant investment is required to keep the LTPT operational, it would make sense to mothball it while investigating options and issues for expanding the NTF to cover these needs.

Also, one hypersonic facility in the Langley hypersonic suite continue to have poor support and should be removed from the list of strategically important facilities. However, the remaining facilities in the Langley suite do serve strategically important needs, so the overall suite cannot be closed. Closing one part of this needed suite may not save much money, however.

Within the 27 facilities rated as *strategically important*, two have not been used recently but are being mothballed as hedges against access and technical issues. First, the Ames Subsonic 12-Foot Pressure Wind Tunnel (PWT) has not been used since our prior study and has been mothballed. Thus, NASA actions to mothball this facility makes sense. The Ames 12-Foot is still the only high-Reynolds number subsonic facility in the United States and is being mothballed as a hedge against the event of lack of access to foreign capabilities. Users have been using facilities in the UK and France for technical reasons; some did not want to pay the price to bring the Ames facility out of mothball and thus also went overseas for testing. This has caused a de facto reliance on foreign facilities for a strategically important U.S. test capability need. Even so, except for Boeing, there have been no strategic agreements with these foreign facilities to ensure security and access. Thus far, there has been no negative effect except for data security concerns, but access being denied in the future or security concerns becoming overwhelming could lead to additional problems.

Second, the Glenn Hypersonic Test Facility (HTF) is strategically important as a technical hedge to preserve its unique, nonvitiating heating capability in the event that vitiation turns out to be a real roadblock in hypersonic propulsion research. HTF has been in various states of non-use and mothballing, but the current mothballing is intended to provide additional preservation.

New Assessment of Simulation Facilities

Our assessment reveals that four of the six simulation facilities under study should be kept and managed as strategically important. One of the other two is scheduled to be replaced by a new facility that is nearing operational capability, and the other is a small, relatively inexpensive

visual flight control laboratory that has no current NASA or Federal Aviation Administration (FAA) needs and very few potential users elsewhere.

Conclusions

The goals, objectives, and actions of NASA's ATP reflect several strategic needs, and ATP's progress appears to be in agreement with our findings. These include identifying and maintaining a minimum set of strategically important test capabilities and identifying shared financial support to keep underused but essential facilities from financial collapse.

Still, NASA and the nation need to continue developing a vision for aeronautics test technology and a plan in response to the new national aeronautics policy (National Science and Technology Council, 2006). Also, national reliance and consolidation remain the next challenges, including between NASA as well as the DoD and between the government and industry.

Further questions and issues remain that were outside the scope of our study but that should be addressed. These include the following: What additional functions should the Strategic Capabilities Assets Program (SCAP) undertake to resolve management issues with its simulation facilities? How can NASA and the DoD best pursue a shared reliance relationship? What kinds of groundwork can be laid now for *international* reliance and consolidation considerations, and can allied cooperation result in noncompetitive infrastructure supporting a competitive development landscape? That is, can we reliably consolidate and jointly share an international test infrastructure in a cooperative reliance model—despite international political or economic differences or tensions—with companies that develop competitive products? What can NASA and the United States do to maintain national and world leadership in aeronautics and in test technology? What kinds of facilities will NASA need in the future as determined by new aeronautics pursuits, such as morphing wings, alternative fuel engines, new hypersonic vehicle concepts, closer aircraft spacing in more crowded U.S. air space, formation flying, and an expanded use of global positioning system (GPS) for flight control?

The nation has been fortunate in that its historical and ongoing test capability investments have resulted in a very flexible infrastructure that continues to serve its testing needs. However, we need to continue asking whether new aeronautics concepts being researched today will require new test capabilities in the future.

Note: Throughout this DB, we use the term *WT/PT facilities* to mean wind tunnel facilities and propulsion test facilities—the type of NASA facilities we assessed. Since individual facilities within this designation can be wind tunnel facilities, propulsion test facilities, or both, *WT/PT facilities* serves as a generic term to encompass them all. That said, when a specific facility is discussed, for clarity, we refer to it by its proper name and, if necessary, include its function (e.g., the *Ames Subsonic 12-Foot Pressure Wind Tunnel*). Also, the terms *test facilities* and *facilities* can be substituted for *WT/PT* and *simulator facilities*. Of course, NASA owns and operates test facilities other than WT/PT and simulator facilities, but our conclusions and recommendations do not apply to them.



A joint effort of
INFRASTRUCTURE, SAFETY, AND ENVIRONMENT
and the
NATIONAL SECURITY RESEARCH DIVISION

An Update of the **Nation's Long-Term Strategic Needs for NASA's Aeronautics Test Facilities**



**Philip S. Antón
Raj Raman
Jan Osburg
James Kallimani**



(Photo sources: NASA Ames, 1995, 2005c)

Note: The photographs on this slide are courtesy of the NASA Ames Research Center. The photograph on the left (SimLabs, 2005c) shows the B747-400 and Advanced Concepts Flight Simulator (ACFS) hexapods in the Ames Crew-Vehicle Systems Research Facility (CVSRF). The photograph on the right shows the inside of the Ames Subsonic 12-Foot Pressure Wind Tunnel—a high-Reynolds number facility—near the turbine blades that drive the air through the tunnel.

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Research team:

- **Dr. Philip S. Antón (co-Principal Investigator)**
- **Dr. Raj Raman (co-Principal Investigator)**
- **Dr. Jan Osburg**
- **James Kallimani**

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Abbreviations

2D	two dimensional
16S	16-Foot Supersonic Wind Tunnel (AEDC)
16T	16-Foot Transonic Wind Tunnel (AEDC)
ACFS	Advanced Concepts Flight Simulator
ASC	Air Force Systems Command
16TT	16-Foot Transonic Tunnel
AEDC	Arnold Engineering and Development Center
AIAA	American Institute of Aeronautics and Astronautics
Ames VMS	Ames Vertical Motion Simulator
APTU	Aero and Propulsion Test Unit (AEDC)
ARMD	Aeronautics Research Mission Directorate
ASC	Aeronautical Systems Center
ASTF	Aeropropulsion Systems Test Facility (AEDC)
AT&L	Acquisition, Technology, and Logistics
ATP	Aeronautics Test Program (NASA)
ATT	Advanced Theater Transport
CEV	Crew Exploration Vehicle
CF ₄	Tetrafluoromethane
CFD	computational fluid dynamics
CIFA	Counterintelligence Field Activity
CLV	Crew Launch Vehicle
CMF	Cockpit Motion Facility (Langley)
CRV	current replacement value

CVSRF	Crew-Vehicle Systems Research Facility (Ames)
DB	documented briefing
DDR&E	Director of Defense Research and Engineering
DDT&E	design, development, testing, and evaluation
DMS	Differential Maneuvering Simulator (Langley)
DoD	Department of Defense
DOF	degrees of freedom
DTRMC	Defense Test Resource Management Center
ECRL	Engine-Components Research Laboratory (Glenn)
ESMD	Exploration Systems Mission Directorate
ETF	Engine Test Facility
ETW	European Transonic Wind
FAA	Federal Aviation Administration
FFC	FutureFlight Central (Ames)
FFS	Full Flight Simulators
FOV	field of view
FTD	Flight Training Devices
G&A	general and administrative
GFD	Generic Flight Deck
GOCO	government-owned, contractor-operated
GPS	global positioning system
HQ	headquarters
HTF	Hypersonic Tunnel Facility (Glenn)
HTT	High-Temperature Tunnel (Langley)
Hyper	hypersonic
Hyper-Prop	hypersonic propulsion integration
HYPULSE	Hypersonic Pulse Facility
IDA	Institute for Defense Analyses
IFD	Integration Flight Deck
IIFD	Integrated Intelligent Flight Deck

IOC	initial operational capability
IRAC	Integrated Resilient Aircraft Control
IRT	Icing Research Tunnel (Glenn)
ISE	Infrastructure, Safety, and Environment (RAND)
IVHM	Integrated Vehicle Health Management
JSF	Joint Strike Fighter
Langley VMS	Langley Visual Motion Simulator
LFC	laminar flow control
LSAM	Lunar Surface Access Module
LTPT	Low-Turbulence Pressure Tunnel (Langley)
M	mothballed
M&S	modeling and simulation
MDA	Missile Defense Agency
MOD	Ministry of Defence (UK)
MW	megawatt
NASA	National Aeronautics and Space Administration
NASP	National Aerospace Plane
NAVAIR	Naval Air Systems Command
NFAC	National Full-Scale Aerodynamics Complex (Ames)
NGATS	Next-Generation Air Transportation System
NSRD	National Security Research Division (RAND)
NSTC	National Science and Technology Council
NTF	National Transonic Facility (Langley)
ONERA	<i>Office National d' Études et de Recherches Aérospatiales</i> (National Office for Aerospace Studies and Research)
OSD	Office of the Secretary of Defense
OSTP	Office of Science and Technology Policy
Prop	propulsion
PSL	Propulsion Simulation Laboratory (Glenn)
PT	propulsion test
PWT	Pressure Wind Tunnel (Ames)

R&D	research and development
RDT&E	research, development, test, and evaluation
RHC	Rotational Hand Controller
RFD	Research Flight Deck
Rn	Reynolds number
Sub	subsonic
SCAP	Strategic Capabilities Assets Program
Super	supersonic
SMD	Science Mission Directorate
S&T	science and technology
TBCC	Turbine-Based Combined Cycle
TDT	Transonic Dynamics Tunnel (Langley)
Tran	transonic
TST	Transportation, Space, and Technology (RAND)
TT	transonic tunnel
UAV	unmanned aerial vehicle
UCAV	unmanned combat aerial vehicle
UK	United Kingdom
UPWT	Unitary Plan Wind Tunnel
U.S.	United States
VTOL	vertical takeoff and landing
WT	wind tunnel
WT/PT	wind tunnel and propulsion test

Background

Outline

- **Background**
- Wind tunnels and propulsion test facilities
- Simulators
- Conclusions
- Appendix A: NASA, DoD, and industry input details
- Appendix B: Simulator descriptions
- Appendix C: Technical discussion of simulation and simulators

RAND

Let us first review the background for this study.

Our Prior Study Assessed National Needs for Wind Tunnels and Propulsion Test Capabilities

- Identify policy options for NASA that efficiently and cost-effectively support national needs for RDT&E of aeronautics technology and vehicles
- Assess NASA's 31 existing major wind tunnel and propulsion test facilities
 - **Conventional wind tunnels**
 - **Subsonic** (Mach range 0–0.6 and $\geq$ 6-foot test section)
 - **Transonic** (Mach range 0.6–1.5 and $\geq$ 4-foot test section)
 - **Supersonic** (Mach range 1.5–5.0 and $\geq$ 2-foot test section)
 - **Hypersonic test facilities**
 - **Hypersonic** (Mach range > 5.0 and $\geq$ 1-foot test section)
 - **Hypersonic propulsion integration test facilities** (Mach range > 5.0 and $\geq$ 1-foot test section)
 - **Direct-connect propulsion test facilities**

(The list of 31 facilities does not include 13 additional NASA facilities that meet these criteria but were already closed in the last decade.)

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The National Aeronautics and Space Administration (NASA) asked RAND to update its prior study of wind tunnel and propulsion test (WT/PT) capabilities (Antón et al., 2004a, 2004b) to see whether changes have occurred in the need for these capabilities and to expand the study to include major simulators. The prior study examined and identified policy options for NASA that efficiently and cost-effectively support national needs for research, development, test, and evaluation, (RDT&E) and for the sustainment of aeronautics technology and vehicles. That study focused on all 31 of NASA's WT/PT capabilities meeting the criteria reflected above but also noted that an additional 13 facilities meeting the criteria had been closed by NASA since the early 1990s.

Main Findings from Our Prior Study

- **NASA's wind tunnel and propulsion test facilities continue to be strategically important to U.S. competitiveness across the military, commercial, and space sectors**
 - Capabilities are generally consistent with national needs, but some investments are needed
 - Many facilities operate at less than full capacity, but closing a last-of-a-kind facility demands an engineering analysis of need
 - Computational fluid dynamics cannot yet replace wind tunnels
- **NASA has done a good job to date of already closing facilities that were redundant or not needed**
- **Management issues are creating real risks**
- **NASA needs to**
 - Develop an aeronautics test technology vision and plan
 - Identify and maintain its minimum set of facilities
 - Identify shared financial support to keep its underutilized but essential facilities from closing due to insufficient use in a year
 - Analyze the viability of a national test facility plan

RAND

The main findings of the prior study were that NASA's WT/PT capabilities remain critical tools for research and production in U.S. aeronautics. The capabilities offered by these facilities are generally consistent with national needs, but some investments are needed. Redundancy was minimal across NASA, and the total costs for operating these facilities were relatively modest. Modeling and simulation capabilities known as computational fluid dynamics (CFD) are helpful, complementary tools that cannot yet replace wind tunnels and will likely not do so for decades. Despite prudent staffing reductions, many of these facilities operate at less than full hardware capacity.

We also concluded that a lack of sustained institutional funding could put NASA facilities more at risk. Thus, we recommended establishing and supporting a minimum set of strategically important facilities to help ensure that long-term needs are not endangered by short-term budget cuts. Some kind of direct funding is needed to support facilities when user funding is low but strategic, long-term reasons dictate keeping the facility.

Finally, we observed that some new investments (especially in hypersonic propulsion test capabilities) may be needed in the future, but more research progress is needed to better understand what new test capabilities will be required to make breakthroughs in air-breathing hypersonic propulsion concepts.

We identified the need for NASA to develop an aeronautics test technology vision and plan to help guide strategic planning. Because some complementary and similar capabilities exist outside NASA, we also recommended that NASA analyze the viability of a national government test facility plan that initially includes the Department of Defense (DoD). Consider-

ing all national facilities in both government and industry to the extent possible in a national test facility plan was also recommended.

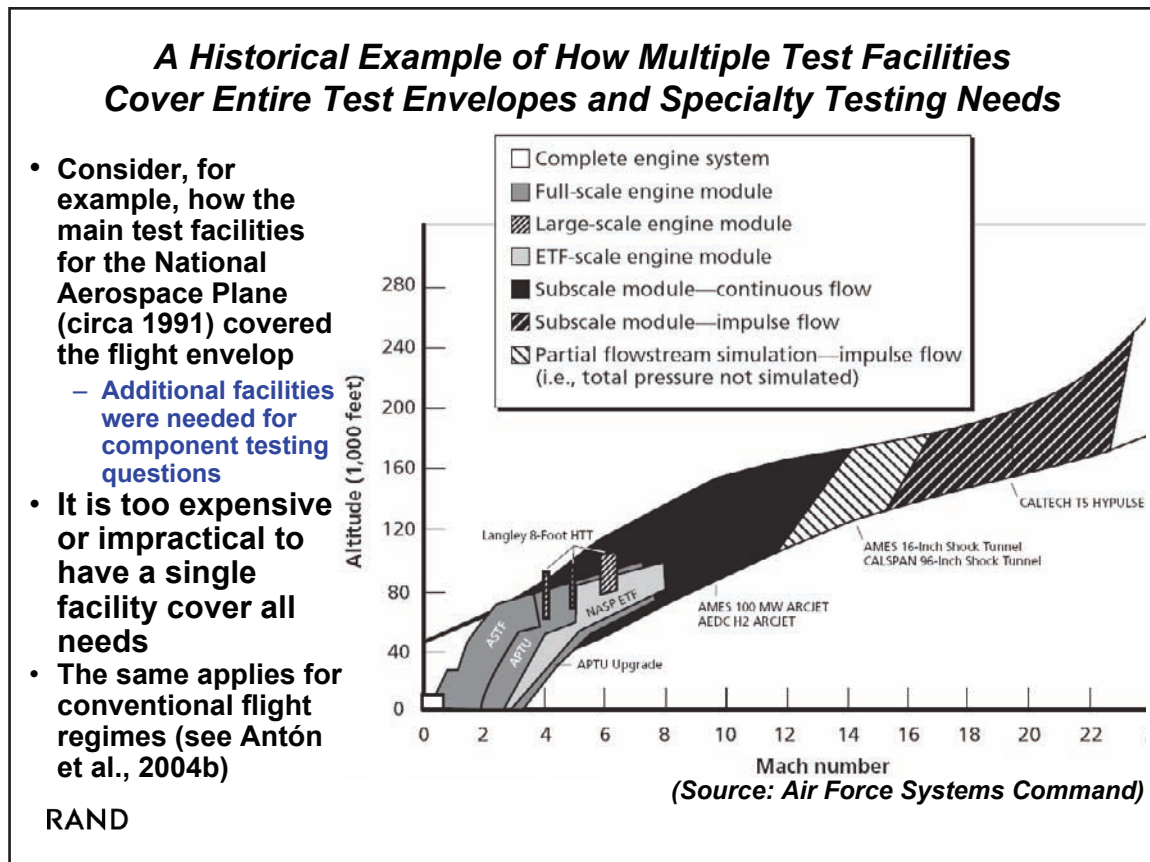
Prior Study Concluded That 29 of 31 NASA Facilities Are Strategically Important for Serving National Needs

Sonic Speed	Location	Facility	Strategically Important?	Sonic Speed/ Propulsion	Location	Facility	Strategically Important?
Sub	Ames	12-Foot	✓	Hyper	Langley	20-Inch CF4	✓
Sub	Ames**	NFAC	✓	Hyper	Langley	20-Inch Air	✓
Sub	Langley	14x22-Foot	✓	Hyper	Langley	31-Inch Air	✓
Sub	Langley	12-Foot Lab	No	Hyper-Prop	Langley	8-Foot HTT	✓
Sub	Langley	20-Foot Spin	✓	Hyper-Prop	Langley	Arc-Heated Scramjet	✓
Sub	Langley	LTPT	✓	Hyper-Prop	Langley	Combustion	✓
Sub	Glenn	9x15-Foot	✓	Hyper-Prop	Langley	Heated Scramjet	✓
Sub	Glenn	Icing WT	✓	Hyper-Prop	Langley	Direct-Connect SS Combustion	✓
Tran	Ames	11-Foot	✓	Hyper-Prop	Langley	15-Inch M6 HTT	✓
Tran	Langley	NTF	✓	Hyper-Prop	Ames	Direct-Connect Arc (M)	✓
Tran	Langley	16TT (closed)	No	Hyper-Prop	Ames	16-Inch Shock (M)	✓
Tran	Langley	TDT	✓	Hyper-Prop	Glenn	HTF (P)	✓
Tran	Glenn	8x6-Foot	✓	Hyper-Prop	GASL***	HYPULSE	✓
Super	Ames	9x7-Foot UPWT	✓	Prop	Glenn	PSL-3	✓
Super	Langley	4-Foot UPWT	✓	Prop	Glenn	PSL-4	✓
Super	Glenn	10x10-Foot	✓	Prop	Glenn	ECRL 2b	✓

RAND

(M) Mothballed by 2004
 ** NASA owned; USAF operated
 *** NASA owned; GASL operated

Our prior study concluded that 29 of the 31 NASA facilities that met our study criteria are strategically important for serving national needs, including two that are mothballed. This slide shows those facilities across the three NASA research centers (Ames, Glenn, and Langley) and across speed and test types: subsonic (Sub), transonic (Tran), supersonic (Super), and hypersonic (Hyper) wind tunnels; hypersonic propulsion integration facilities (Hyper-Prop); and direct-connect propulsion (Prop) test facilities. The two facilities not deemed strategically important are shaded grey: the Langley 12-Foot atmospheric laboratory and the Langley 16-Foot Transonic Tunnel (16TT).



Why do we need so many test facilities?

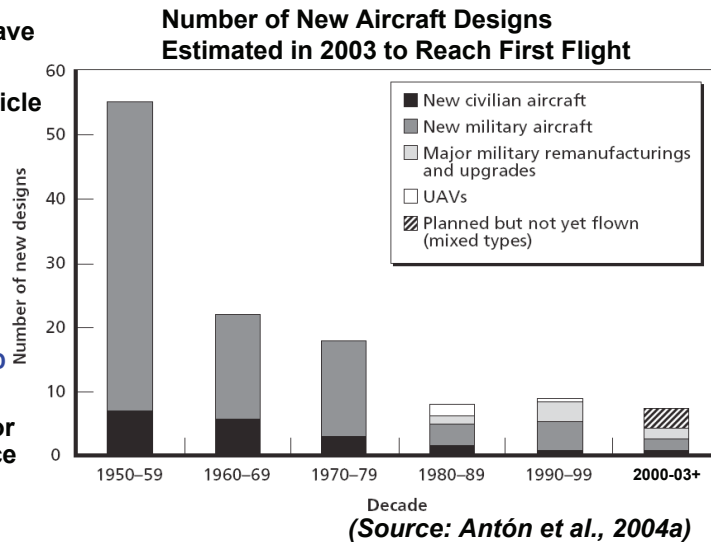
It is simply too expensive or impractical to build a single facility to cover all capability needs. Smaller tests in a large facility are too expensive, so prudent decisions have been made over the decades to invest in a range of capabilities and sizes to provide strategically important test capabilities that cover the test envelopes at reasonable prices.

For example, consider the historical graph shown in the slide above. Here, the Mach number and altitude test capabilities of various facilities are plotted against the flight envelope for the National Aerospace Plane (NASP) to show how different facilities are needed to address different parts of the test envelope. Although the NASP program is now defunct, this slide shows how different facilities cover different parts of a flight envelope. Current hypersonic and space access programs also grapple with how to cover a range of Mach numbers and altitudes. Additional charts could be developed for more conventional subsonic, transonic, and supersonic regimes. See Antón et al. (2004b) for tables showing the capabilities and shortcomings of different facilities in each speed regime and how no one facility can meet all general-purpose and special-purpose testing needs.

Fewer New Aircraft Designs Lead to Variable and Sometimes Low Facility Use

- **Stark decline in vehicle developments since 1950s**
- **BUT no new vehicle classes have been eliminated**
- **AND some new aerospace vehicle concepts are emerging**
 - UAV/UCAVs
 - Air-breathing hypersonic missiles or planes
 - VTOL
- **Most NASA redundancy has been eliminated**
 - Some redundancy with the DoD and industry will be noted later
- **Therefore, WT/PT and simulator capabilities required to produce these vehicles**
 - Are having variable and sometimes low utilization

RAND



Despite overall declines in aerospace research and aerospace vehicle production rates, the nation continues to pursue performance improvements in past aerospace vehicle types while exploring new vehicles and concepts, resulting in demands for aeronautics prediction capabilities.

The argument that we do not require much aeronautics prediction capacity from WT/PT facilities is driven mostly by the sense that development and production activities are declining from historical highs. And, in fact, this plot from our prior study (counting the number of new aircraft designs reaching first flight per decade) shows that the number of new aerospace vehicles put into production has indeed decreased from historic highs. These numbers reinforce what has been generally expressed in the aeronautics community—that fewer vehicles are being put into production today than in the past. As shown in the slide, the number of civilian aircraft starts has declined from about eight per decade in the 1950s to about one per decade in the 1990s and in the current decade. Military aircraft starts have also slowed (especially when compared with the 1950s).

However, the nature of current vehicle starts is also changing. Manned military aircraft programs are larger and more complex than their predecessors, whereas unmanned aircraft are becoming the largest part of military aircraft starts.

Although the slide does show a rapid decline, it also helps to make a more subtle point: *No vehicle classes have been eliminated from future needs, and each class will continue to require empirical prediction of airflow behavior across a range of design considerations.* Even beyond the existing programs, it is clear that the country will eventually need to produce some vehicles in each existing class. For example, a new bomber will sooner or later be produced even though it is not yet certain how soon a new USAF bomber program will be started, and the Army

and commercial industry will not forgo rotorcraft. Thus, *the aeronautics prediction capabilities required to produce these vehicles (no matter their production rate) must be preserved or be able to be regenerated in a timely manner, or the country will risk losing the ability to produce them without dependency on foreign cooperation and access to their test capabilities.*

When redundancy is eliminated and it is infeasible to create a new facility on demand, utilization becomes an indicator not of redundancy but of management challenges to preserve important capabilities. Management is challenged to keep the remaining low-use facilities financially viable and technically sound for future needs in the face of low revenues from testing.

Not only does this imply that demand is lower, but the low frequency of new designs means that we have gaps between programs that lead to periodic lulls in facility demand.

Furthermore, the mix of vehicles being explored is expanding. New unmanned aerial vehicles (UAVs), unmanned combat aerial vehicles (UCAVs), air-breathing (as opposed to rocket-propelled) hypersonic missiles and reconnaissance planes, and vertical takeoff and landing (VTOL) concepts are being explored and developed. Therefore, the United States will need to satisfy the state-of-the-art aeronautics prediction capability needs emerging from these new vehicle types. NASA's WT/PT capabilities play a role in serving these needs. The survey responses indicated that design engineers were thinking about these kinds of vehicles when they discussed the kind of test capabilities they need generally for these classes of vehicles.

Our prior study also found that NASA has reduced its WT/PT facilities since the early 1990s. We are now down to our last facility (or in cases of critical capability types, two facilities) of each type required to pursue these various vehicle classes, leading to variable and sometimes low use of strategically important facilities. In later slides, we will show that there is some redundancy between NASA and DoD facilities, leading to a recommendation to continue pursuing consolidation and reliance efforts between the two.

A Long-Term, Strategic View of Major Test Facilities Is Warranted Due to Construction Costs and Times

- **Current replacement value (CRV) of 26 of the 31 test facilities found in the NASA Real Property Database totaled about \$2.5 billion**
 - **CRV underestimates the actual cost of replacing WT/PT facilities because they are more complex facilities than the building types used in the baselines for general engineering economics**
- **Construction cost for the large subsonic and transonic facilities proposed in the 1994 National Facility Study ran in the \$2–3 billion range**
- **These types of major aeronautics facilities have historically taken over 10 years to construct, necessitating a long-term view, not counting the time to**
 - **Develop the facility technology**
 - **Defend the program**
 - **Acquire funding from Congress**

RAND

It is important to take a long-term, strategic view when assessing these types of major aeronautics test facilities, because construction times can be long and construction costs can be substantial.

In our prior study, for example, we found that the current replacement value (CRV) of 26 of the 31 test facilities in the NASA Real Property Database totaled about \$2.5 billion (Antón et al., 2004b, p. 131). As high as this number is, facility managers believe that the CRV underestimates the actual cost of replacing WT/PT facilities, because they are more complex buildings than the building types used in baselines for general engineering economics.

Construction estimates for the large subsonic and transonic facilities proposed in the National Facility Study (NASA, 1994) were in the \$2 billion to \$3 billion range (depending on the exact configuration being discussed) (Antón et al., 2004b, p. 131).

In addition to high cost, these type of major aeronautics facilities have historically taken more than 10 years to construct, necessitating a long-term view. This estimate is based on data obtained from the U.S. Air Force (USAF) for DoD WT/PT facilities and from oral communication with NASA managers regarding historical construction times for NASA facilities (see Antón et al., 2004b). This time period does not even count the time to develop the facility technology, defend the program in programmatic and budgetary planning, and acquire funding from Congress (Antón et al., 2004b, pp. 131–132). Thus, if a new vehicle program required an unanticipated new major test capability, construction time for a new facility could cause a delay in that program.

Low-Use Strategically Important Capabilities Risk Loss under Closure or Mothballing

- **Low-use facilities can be closed for long periods, but cost savings may be lower than expected and capabilities will degrade quickly**
 - Closures can reduce contractor labor and variable center costs
 - Cost of any infrastructure and some civil servant staff shared with other open facilities may not be reduced when a single facility is closed
 - Possibly higher testing costs, travel, models, etc., for programs
 - Facility hardware and equipment may degrade quickly without a level of mothballed maintenance
- **Mothballing a strategically important facility is preferred to closure, but mothballing still involves risk**
 - Harder to reconstitute workforce expertise required to safely and effectively operate the facility as time goes on
 - Hardware will still likely have some degradation (depending on what is done in mothball preservation)
- **An alternative is to provide strategic financial support for periodic use of the capabilities to exercise staff and equipment to maintain knowledge, skills, and equipment**
 - Example: Funding a few academic research tests per year
 - Will want to make sure that these capabilities are still strategically important if such strategic resources are to be obtained and applied

RAND

Given that utilization can sometimes be very infrequent, one may ask why mothballing is not more commonly used to reduce financial burdens in between uses. We found in our prior study (Antón et al., 2004a) the following issues with mothballing.

Closures can reduce contractor labor and variable center costs, but additional costs to NASA remain or are incurred. These costs can include higher testing costs at alternative facilities, increased travel expenses, and the need to develop new models. There are also the nonrecurring and recurring costs of mothballing, or the nonrecurring costs to abandon and demolish a facility.

Also, costs remain associated with infrastructure shared with other facilities that are not eliminated. Many civil servant staffing costs are not saved when those staff are already reallocated to different facilities, but some maintenance labor would be reduced.

From a hardware perspective, although mothballing a strategically important facility is preferred to abandonment, we found that mothballing involves the loss of workforce expertise required to safely and effectively operate the facility.

Thus, mothballing is not an effective solution for dealing with long periods of low use, and it puts facilities at risk.

Policy and Management Actions to Date Recognized These Issues

Prior Conclusions

1. NASA's wind tunnel and propulsion test capabilities remain critical tools for research and production in U.S. aeronautics
2. Establishing and supporting a minimum set of strategically important facilities can ensure that long-term needs are not endangered by short-term gains
 - Direct funding is probably needed to support facilities when user funding is low
3. Some investments (e.g., hypersonic propulsion) may be needed

Actions to date:

- ***Congress and NASA continued to support aeronautics test facilities***
- ***NASA established the Aeronautics Test Program (ATP)***
 - *Provide coordinated management*
 - *Continue to review the importance of each facility*
 - *Support for fixed costs to “keep doors open”*
 - *Maintenance and improvements*
 - *Test technology research*
- ***ATP making some minor improvements***
 - *Specific new needs in hypersonics test facilities still to be determined*

RAND

We can now map policy and management actions to date against the conclusions and recommendations from our prior study to provide a picture of current trends.

First, Congress and NASA recognized the strategic importance of the facilities we assessed. See the following slide.

Second, NASA established a new, separate program under the Aeronautics Research Mission Directorate (ARMD) called the Aeronautics Test Program (ATP) to provide coordinated management of its test facilities, continue to review the importance of each facility, provide shared support for the fixed costs to “keep the doors open,” provide maintenance and improvements to keep these facilities functioning and technically current, and fund test technology research.

Finally, it is still not clear what new hypersonic test facilities are needed, so no actions have been taken on this point.

Congress Requested an Update That Led to Our Current Study

- **Congress recognized the importance of empirical aeronautics test facilities**
 - **Directed NASA not to close any of the 29 facilities we assessed as strategically important**
 - **Requested OSTP to conduct an updated review before any facilities can be closed**
 - **Asked for an assessment of specific simulation capabilities**
- **OSTP and NASA HQ requested RAND to conduct the current study to inform OSTP's update and response to Congress**

RAND

The National Aeronautics and Space Administration Authorization Act of 2005 (P.L. 109-155), under “NASA Aeronautics Test Facilities and Simulators” (§101[j]) directed that “the Director of the Office of Science and Technology Policy [OSTP] shall commission an independent review of the Nation’s long-term strategic needs for aeronautics test facilities” (House Conference Report, 2005a). NASA was directed not to close any of the facilities listed as strategically important in our prior study (Antón et al., 2004a) unless that subsequent strategic review by OSTP established that the facilities to be closed are no longer needed strategically. This congressional direction led to NASA’s funding of the current study to help inform OSTP and NASA’s management decisions.

Congress also asked OSTP about major aeronautics simulators, leading to the addition of simulators to our study criteria (House Conference Report, 2005b). These simulators include NASA’s large-motion simulators and one visual simulation facility, which we included in our examination.

Our Current Study Sought to Update the List of Strategically Important Facilities

- **Focus**
 - Same NASA wind tunnel and propulsion test (WT/PT) facilities
 - Six major aeronautics motion and visualization simulators
- **Approach**
 - **WT/PTs: Look for changes in advocacy and technical capabilities**
 - Strategic needs in current NASA research programs (aeronautics and space)
 - Leveraged DTRMC* identification of “critical” DoD needs for NASA’s facilities
 - Examined user community aeronautics engineering descriptions of test capability needs and facility characterizations
 - Examined detailed (unpublished) information from DTRMC study
 - Resurveyed DoD and industry users (aeronautics engineers)
 - **Simulators: New assessment of advocacy and technical capabilities**

* Defense Test Resource Management Center

RAND

Our current study focuses on the 29 major NASA WT/PT facilities that we categorized as strategically important to national needs in our prior study, plus six NASA simulators.

To identify any changes in national WT/PT needs since our last study, we resurveyed the same DoD service and industry respondents using the same questions to understand their long-term strategic needs (see Antón et al., 2004b, pp. 120–129). To identify specific differences, respondents were sent their own prior survey responses and were asked to identify any changes since 2003.

We also employed the recent DoD study of “critical” facilities conducted by the Defense Test Resource Management Center (see AT&L, 2007), including a detailed look at the unpublished information collected for that study on facilities that may be strategically important but not deemed critical.

Finally, we solicited information on strategic needs from the current NASA research programs (aeronautics and space) and reviewed their program plans.

To assess simulator needs and capabilities, we reviewed simulator types and their general use and asked NASA, DoD, and industry users to describe their strategic uses for these capabilities.

These assessments involved the application of our WT/PT expertise developed in our prior study. Since the changes were minimal on the WT/PT front, we did not need to engage technical experts on new WT/PT issues. On the simulation front, however, we employed the expertise of our in-house aeronautical engineer and the research literature on simulation.

DoD Needs Reflect Both “Critical” and Other Strategic Needs

- **DTRMC study effort provided inputs on facilities that are**
 - **“Critical”: defined as**
 - If not available to DoD pose an unacceptable risk to research, development, modernization and sustainment of the weapon systems supporting the defense mission. Risk may be an expression of cost, security, or time.
NASA Aeronautics Facilities Critical to DoD (AT&L, 2007)
 - **Other important—but not critical—strategic needs (unpublished)**
- **We summarized “critical” plus other strategic needs not meeting the criticality threshold**
 - **Resurveying DoD armed services**
 - **Read detailed, unpublished responses from the DTRMC study**

RAND

Our summary of DoD government needs reflects what the DoD has officially designated as “critical” and identifies additional needs and uses that did not rise to this official designation in the DTRMC study (AT&L, 2007). In addition to using the DoD’s designation of critical facilities, we sought to draw a picture of future needs and potential uses by incorporating the views of advocates from NASA programs and from industry.

We Received WT/PT Survey Inputs from All Prior DoD and Industry Respondents Plus Two New Ones

DoD:

- **Army**
 - UAVs
 - Missiles
- **Air Force ASC**
(Aeronautical Systems Center)
- **Navy NAVAIR**
(Naval Air Systems Command)

Industry (propulsion):

- **General Electric**
- **Pratt & Whitney**
- ***Rolls Royce****
- **Williams International**

Industry:

- **Bell Helicopter**
- **Boeing**
 - Commercial (transport aircraft)
 - Tactical aircraft (manned, UCAV)
 - So. Calif (ATT, high-speed vehicles)
 - Hypersonic programs
 - *Rotorcraft**
- ***Cessna****
- **Gulfstream (business jets)**
- **Lockheed Martin**
 - Tactical and UCAV
- **Northrop Grumman**
 - UAV and UCAV
- **Raytheon**
 - Aircraft, business jets
 - Missiles
- **Sikorsky helicopter**

**Did not participate in our original survey*

RAND

We resurveyed DoD, aerospace industry, and propulsion-industry organizations outside NASA shown on this slide. The respondents were aeronautics design experts who understand the testing requirements for the vehicles their organization produces. They also understood the capabilities of and trade-offs between NASA and other wind tunnels and propulsion test facilities. The summary results from their responses are listed on the following slides.

For Simulator Needs and Advocacy, We Talked to NASA and DoD Research Users While Reviewing Existing Program Plans

NASA

- Reviewed NASA ARMD and Exploration Systems Mission Directorate (ESMD) research programs

DoD

- Reviewed DTRMC study (AT&L, 2007)
- Interviewed
 - NASA Langley researchers and managers
 - USAF, NAVAIR, and Army researchers at NASA

Industry

- Discussions with simulator facility management
 - No stable set of users was identified

RAND

For the simulator needs and advocacy, we talked to resident NASA and DoD researchers to identify their testing needs. We also reviewed existing NASA program plans as well as the DTRMC study (AT&L, 2007).

To assess industry's needs for NASA's simulators, we interviewed the managers of each NASA simulation facility to try to identify industry users. However, we found that the user base was inconsistent and aperiodic. Industry has many dedicated in-house simulation capabilities that are platform-specific and used for product development and pilot training, so they turn to NASA's simulators only for aperiodic research uses.

Strategically Important Capabilities Were Determined Based on Users' Advocacies, Facility Shortcomings, and Uniqueness within NASA

- “Strategically important” capabilities serve needs identified for:
 - Current NASA program needs
 - DoD “critical” needs (DTRMC study report)
 - Expert user inputs on capability importance, shortcomings, and alternatives
- Asked users to explain their long-term strategic testing needs
 - Consider the generic types of vehicles they work on
 - Informed by current projects
 - Also looking to future potential vehicles generally
 - Explain what facilities meet their testing needs
 - Technical capabilities, cost, availability, workforce aspects
- Assessed the strength of the advocacies
 - Breadth of support across sectors
 - Importance in a single sector or vehicle class
- Assessed alternatives within NASA

Importance is based on an engineering perspective derived from vehicle classes the United States produces

- Not from a national facility plan or federal budget decisions

RAND

We identify a capability as “strategically important” based on three factors: the strength of users’ advocacies and descriptions of their long-term strategic testing needs; any revealed capability shortcomings or issues (e.g., flow quality concerns or condition in mothball); and uniqueness within NASA in meeting testing needs (e.g., are there better alternative capabilities elsewhere within NASA).

We measured and derived national need and strategic importance from an engineering perspective, asking design engineers and users to explain their long-term strategic testing needs as determined by the types of vehicles on which they work generally. This would include not only current vehicle projects but future vehicle classes that might be produced. This discussion explored not only the technical capabilities that might be needed and used but other factors that affect engineers’ decisions to use specific facilities, including cost, availability, and workforce quality.

We then analyzed the responses to assess the strength of the needs. Strategically important capabilities were those that serve existing NASA programs and their long-term plans, DoD needs critical to meeting its mission, or other DoD and industry needs. Our analysis judged the needs either by their strength in a single sector or by their breadth across multiple sectors. Strategically important capabilities also do not have better alternatives within NASA and generally do not have significant adverse technical issues.

The analytic method used in this study does *not* rely on an explicit and detailed national strategy plan for aeronautics test capabilities. This is because such a plan still does not exist and because this study is intended to help inform the creation of such a plan. Also, aeronautics test facilities and operations are only partially funded by specific line items in the NASA budget.

Thus, the study's determination of facility needs and our resulting conclusions and recommendations are not based on the federal budget process as a direct indicator of policy dictates of facility need. As with a national plan, this study is intended to help inform that process rather than to be driven by it.

Finally, although the study focused on national needs and NASA's aeronautics test infrastructure, national needs are not dictated or met solely by NASA's test infrastructure; DoD, U.S. industry, and foreign facilities also serve many national needs. However, our study was not chartered or resourced to examine data sets for these alternative facilities to fully understand consolidation opportunities between NASA and non-NASA WT infrastructures. Nonetheless, our findings reveal that such a broader study is important and warranted.

We Sought to Address Methodological Biases and Gaps

- **Concern: Long-term testing needs are unpredictable**
 - **Mitigation: Asked respondents to consider testing needs related to the class of vehicles they design rather than just current programs**
 - Examples: Civil and military transport, business jets, general aviation, fighters, bombers, UAVs, rotorcraft, missiles, planetary air vehicles, engines, air-breathing hypersonic vehicles
- **Concern: Conservative bias may result from users not being forced to pay for advocated facilities**
 - **Mitigation: Examined engineering justifications and reasoning in the responses to understand**
 - Technical uses for specific capabilities and their importance
 - Practical decisions (cost, availability) that drive the use of certain facilities
 - Alternatives and implications of lack of testing capabilities
- **Concern: Prior list was large and not prioritized**
 - **Mitigation: Sought ways to help inform facility prioritization**

RAND

We took specific steps to try to address methodological biases and gaps that could arise from the study approach.

First, long-term testing needs are unpredictable, because test plans in current programs both are unstable and often do not extend more than 6–12 months into the future. Also, vehicle programs themselves come and go over the years in the federal budget process and in industry planning, so there is uncertainty about what specific vehicles may be researched, developed, and produced in a certain period. To help mitigate this concern, we asked respondents to consider testing needs related to the class of vehicles they design rather than focusing solely on current programs. Thus, we discussed what testing needs arise generally from vehicles and systems such as civil and military transport, business jets, general aviation, fighters, bombers, UAVs, rotorcraft, missiles, planetary air vehicles, engines, and air-breathing hypersonic vehicles.

Second, users responding to our survey were not being asked to pay for facilities that they advocate using. This condition, of course, can bias the findings, because these assessments may reflect more what engineers determine is strategically important than what program managers are willing to spend on testing because of program budget constraints. To help mitigate this concern, we analyzed not only the technical justifications and reasoning in the responses relating to a certain testing capability but also the associated aspects of cost, availability, workforce quality, and alternative facilities to understand the process through which program managers go when deciding to pay for a test at a facility. This approach allowed us to understand what facilities are used for, the practical decisions (cost, availability) that drive users to certain facilities, and the alternatives and implications of lack of testing capabilities.

Third, we realize that our prior study provided a mostly unprioritized list of strategically important capabilities. We sought ways to help provide relative importance information and discussion in this study, such as determining the technical importance of the capability, its uniqueness, the lack of alternative approaches, the cost of alternatives, and the strength and breadth of support (e.g., whether the DoD deemed a capability as critical to its mission).

Part of the challenge in doing this is that there is no accredited textbook in aeronautics that lays out what happens when you do not test in a certain part of the flight envelope or test a certain aspect of the vehicle in question. There also are no cost-benefit data available to inform the question of consequences if a certain test is conducted (or not). We, therefore, have to rely on expert input to understand the trade-offs. We do know, however, that the design community has been under intense budgetary pressures for decades, and designers' responses reflected their insights into cost-benefit trade-offs not only in certain tests but in the selection of a NASA versus non-NASA facility for a test.

Wind Tunnels and Propulsion Test Facilities

Outline

- Background
- Wind tunnels and propulsion test facilities
- Simulators
- Conclusions
- Appendix A: NASA, DoD, and industry input details
- Appendix B: Simulator descriptions
- Appendix C: Technical discussion of simulation and simulators

RAND

Let us now examine our findings for the WT/PTs, including program needs from NASA's new programs, the DoD's assessment, and information gathered from resurveying the DoD and industry.

Most Facilities We Rated as Strategically Important in Our Prior Study Were Considered Primary by ATP

Strategically Important?	Location	ATP Assets		Outside ATP
		Primary	Non-Primary	
Yes	Ames	• 11-Foot Unitary Transonic • 9x7-Foot Unitary Supersonic	• 12-Foot Pressure (M) • NFAC (DoD operated)	• 16-Inch Shock (M) • Direct Connect (M)
	Glenn	• IRT Subsonic Icing Research • 9x15-Foot Subsonic Propulsion • 10x10 Supersonic Propulsion • PSL-3 propulsion • PSL-4 propulsion	• HTF Hypersonic (P) • 8x6 Transonic Propulsion • ECRL 2b propulsion lab	
	Langley	• 14x22-Foot Subsonic • 20-foot Vertical Spin • NTF National Transonic Facility • TDT Transonic Dynamics • 4-Foot Unitary Supersonic • 8-Foot HTT hypersonic • 20-Inch M6 CF₄ • 20-Inch M6 Air • 31-Inch M10 Air • 15-Inch M6 Propulsion HTT	• LTPT low-turbulence 2D	• Arc-Heated Scramjet propulsion • Combustion Scramjet • Supersonic Combustion • HYPULSE (GASL operated)
No	Langley		• 16-Foot Transonic Tunnel	• 12-Foot Lab

RAND*(ATP ratings as of 2007)*

(M) Mothballed by start of current study

(P) Mothball preservation started during current study

As mentioned in Chapter One, NASA's ATP provides strategic oversight and management of nearly all the WT/PTs in our study. Most of the facilities that we rated as strategically important in our prior study (Antón et al., 2004a, 2004b) were considered "primary" by ATP in 2007, when our study began. Primary facilities receive first consideration when it comes to distributing ATP support resources. As one would expect from a prioritization process, some of the facilities we rated as strategically important are not rated as primary because of their wider importance.

Also, a few facilities are not currently listed in the ATP asset list. These include two mothballed facilities at Ames, three propulsion integration test cells at Langley, and the HYPULSE facility owned by NASA but operated by GASL.

Our Current Study Especially Sought to Understand Assets Rated Low by NASA ATP

Strategically Important?	Location	ATP Assets		Outside ATP
		Primary	Non-Primary	
Yes	Ames	• 11-Foot Unitary Transonic • 9x7-Foot Unitary Supersonic	• 12-Foot Pressure (M) • NFAC (DoD operated)	• 16-Inch Shock (M) • Direct Connect (M)
	Glenn	• IRT Subsonic Icing Research • 9x15-Foot Subsonic Propulsion • 10x10 Supersonic Propulsion • PSL-3 propulsion • PSL-4 propulsion	• HTF Hypersonic (P) • 8x6 Transonic Propulsion • ECRL 2b propulsion lab	
	Langley	• 14x22-Foot Subsonic • 20-foot Vertical Spin • NTF National Transonic Facility • TDT Transonic Dynamics • 4-Foot Unitary Supersonic • 8-Foot HTT hypersonic • 20-Inch M6 CF₄ • 20-Inch M6 Air • 31-Inch M10 Air • 15-Inch M6 Propulsion HTT	• LTPT low-turbulence 2D	• Arc-Heated Scramjet propulsion • Combustion Scramjet • Supersonic Combustion • HYPULSE (GASL operated)
No	Langley		• 16-Foot Transonic Tunnel	• 12-Foot Lab

RAND*(ATP ratings as of 2007)*

(M) Mothballed by start of current study

(P) Mothball preservation started during current study

Because this study focused on what may have changed since we completed our prior study, the most interesting stories and potential changes include those lying near the lower end of ATP's prioritization list and those that fall outside the current ATP asset list. We also focused on the Langley Supersonic 4-Foot Unitary Supersonic WT complex because our prior study determined that it was used very little.

Usage, Need, and Operation Shifts Have Modified Some of the WT/PT Landscape

- **Some WT/PTs have had no recent utilizations (despite unique capabilities)**
 - Ames 12-Foot high-Rn Pressure WT is now mothballed
 - Glenn HTF is in the process of being mothballed
 - **Other utilizations were low in our last study and needed attention in our survey update**
 - Langley LTPT
 - Langley 4-Foot Unitary Supersonic
 - **Some are operated by others**
 - Ames NFAC (by DoD/AEDC)
 - Langley HYPULSE (by GASL)
 - **Two hypersonic propulsion-integration facilities remain mothballed**
 - Ames Direct-Connect Arc Facility
 - Ames 16-Inch Shock Tunnel
 - **Some are small laboratories**
 - ECRL 2b for rotorcraft testing
 - Langley 12-Foot atmospheric lab
 - **One rated not strategically important has closed: Langley 16-Foot TT**
- RAND

Some of the lower ATP prioritizations can be understood by information presented in our previous study, but others stem from usage, need, and operational shifts since then.

Some WT/PTs have had no recent use despite having unique capabilities that are strategically important for the long term. The Ames 12-Foot remains the only high-Reynolds number (Rn) subsonic facility in the United States. However, because of circumstances discussed in depth in our prior study, it has remained unused. Given the recognition of the importance of such a capability and the fact that this is the only such U.S. capability, ATP has decided to mothball the facility—not to eliminate the capability but to preserve what it can given its lack of use. Similarly, the Glenn HTF, which has also gone through a long spell of no use, is in the process of being mothballed to preserve what can be saved.

Other recent utilization trends were unclear and needed further analysis. These included the Langley LTPT for two-dimensional tests and the Langley 4-Foot Unitary Supersonic complex.

Two other facilities are operated by non-NASA entities; thus, much of the responsibility for their technical condition and operation has been delegated to those entities. The Ames National Full-Scale Aerodynamics Complex (NFAC) and its two test sections (80x120-Foot and 40x80-Foot), while still owned by NASA, are now operated by the U.S. Air Force's Arnold Engineering and Development Center (AEDC). The DoD and the AEDC are investing resources to improve the NFAC's technical condition after NASA mothballed it. A second facility, the Langley Hypersonic Pulse Facility (HYPULSE) is a government-owned, contractor-operated (GOCO) facility in Ronkonkoma, New York; it is owned by NASA but operated by the GASL division of Allied Aerospace. Allied Aerospace was formed in 1999 by the merger

of GASL Inc., Dynamic Engineering Inc., and Micro Craft Inc. (see Jacobs, 2006). The rest of the facilities are government-owned and -managed, often with contractor support involved in the operation of the facility.

Two hypersonic propulsion-integration facilities—the Ames Direct-Connect Arc Facility and the Ames 16-Inch Shock Tunnel—remain mothballed. Despite their importance in the National Aerospace Plane program (see Antón et al., 2004b, p. 81), the need for these facilities has not risen to a level at which they have been reactivated.

Some of the nonprimary facilities are actually small laboratories and, thus, tend to receive less strategic weight than do the larger facilities. These include the Glenn Engine-Components Research Lab Cell 2B (ECRL 2B) for rotorcraft testing and the Langley 12-Foot atmospheric (low-Rn) laboratory.

Finally, one facility that we had rated as not being strategically important in the prior study has closed as we expected: the Langley 16-Foot Transonic Tunnel (16TT).

Recently, NASA's ARMD Research Has Shifted from Demonstrators to Fundamental Aeronautics Research

- **ARMD now has three main research thrusts (in addition to ATP)**
 - **Aviation Safety**
 - Aircraft Aging and Durability
 - Integrated Vehicle Health Management (IVHM)
 - Integrated Resilient Aircraft Control (IRAC)
 - Integrated Intelligent Flight Deck (IIFD)
 - **Next-Generation Air Transportation System**
 - Air Traffic Management: Airportal
 - Air Traffic Management: Airspace
 - **Fundamental Aeronautics Program**
 - Fixed-Wing Subsonic
 - Rotary-Wing Subsonic
 - Supersonic
 - Hypersonic
- **In addition to ARMD, we contacted Exploration Systems Mission Directorate (ESMD) and Science Mission Directorate (SMD) for any aeronautics testing needs**

RAND

Since our previous study, ARMD at NASA has shifted direction to foundational aeronautics research and away from demonstrator programs. This restructuring has focused research in three main areas: Aviation Safety, the Next-Generation Air Transportation System, and the Fundamental Aeronautics Program. Under Aviation Safety, the four programs are Aircraft Aging and Durability, Integrated Vehicle Health Management, Integrated Resilient Aircraft Control, and Integrated Intelligent Flight Deck. Next-Generation Air Transportation System comprises Air Traffic Management research in Airportal and Airspace. The Fundamental Aeronautics Program has four research areas: Fixed- and Rotary-Wing Subsonic, Supersonic, and Hypersonic Programs.

Besides ARMD, we also contacted the Exploration Systems Mission Directorate and Science Mission Directorate to search for any aeronautics testing needs that may have arisen or that they can envision arising from their missions.

Program Restructurings Affected Some NASA Advocacies

Sonic Speed	Location	Facility	Prior Study	Current NASA Advocacies
Sub	Ames	12-Foot (M)		
Sub	Ames***	NFAC	✓	✓
Sub	Langley	14x22-Foot	✓	✓
Sub	Langley	12-Foot Lab	✓ *	✓ *
Sub	Langley	20-Foot Spin		✓ Added
Sub	Langley	LTPT	✓	Dropped
Sub	Glenn	9x15-Foot	✓	✓
Sub	Glenn	Icing WT	✓	✓
Tran	Ames	11-Foot		✓ Added
Tran	Langley	NTF	✓	✓
Tran	Langley	16TT (Closed)	✓	—
Tran	Langley	TDT	✓	✓
Tran	Glenn	8x6-Foot	✓	✓
Super	Ames	9x7-Foot UPWT		✓ Added
Super	Langley	4-Foot UPWT	✓	✓
Super	Glenn	10x10-Foot	✓	✓

* Some usage exists due to very low costs, but technical capabilities are inferior and alternatives exist

(M) Mothballed by start of current study
*** NASA owned; USAF operated

RAND

This slide summarizes the results of our examination of the needs from NASA's newly restructured research programs across ARMD and space systems for the subsonic (Sub), transonic (Tran), and supersonic (Super) speed regimes at the NASA Ames, Glenn, and Langley research centers. Three additional facilities now have needs in the NASA research program, and one has been dropped. The Langley LTPT is no longer strategically important, and there is an additional need for the Langley 20-Foot Spin Subsonic, as well as for the Ames 11-Foot Transonic Tunnel and the Ames 9x7-Foot Supersonic Tunnel.

There have also been some changes in the status of NASA's facilities since our previous study. The 12-Foot High Reynolds Number Subsonic Tunnel at Ames is mothballed, and the Langley 16-Foot Transonic Tunnel is closed. The two facilities determined in the prior study not to be strategically important (the Langley 12-Foot Laboratory and the Langley 16TT) are shown in shaded rows in the slide.

Program Restructurings Affected Some NASA Advocacies (Concluded)

Sonic Speed/ Propulsion	Location	Facility	Prior Study	Current NASA Advocacies
Hyper	Langley	20-Inch CF4	✓	✓
Hyper	Langley	20-Inch Air	✓	✓
Hyper	Langley	31-Inch Air	✓	✓
Hyper-Prop	Langley	8-Foot HTT	✓	✓
Hyper-Prop	Langley	Arc-Heated Scramjet		✓ Added
Hyper-Prop	Langley	Combustion Heated Scramjet		✓ Added
Hyper-Prop	Langley	Direct-Connect SS Combustion		✓ Added
Hyper-Prop	Langley	15-Inch M6 HTT		
Hyper-Prop	Ames	Direct-Connect Arc (M)		✓ Added
Hyper-Prop	Ames	16-Inch Shock (M)		
Hyper-Prop	Glenn	HTF (P)	✓	Dropped
Hyper-Prop	GASL ***	HYPULSE		
Hyper-Prop	Glenn	PSL-4	✓	✓
Prop	Glenn	PSL-3	✓	Dropped
Prop	Glenn	ECRL 2b		✓ Added

(M) Mothballed by start of current study

(P) Mothball preservation started during current study

*** NASA owned; GASL operated

RAND

This slide summarizes the results from our examination of the needs from NASA's newly restructured research programs across ARMD and space systems for the hypersonic wind tunnels (Hyper), hypersonic propulsion-integration facilities (Hyper-Prop), and the direct-connect propulsion test facilities (Prop) at the NASA Ames, Glenn, and Langley research centers. In hypersonics, there has generally been an increase in use as the programs have shifted to foundational research. More specifically, the Langley Arc-Heated Scramjet and the Langley Combustion Heated Scramjet facilities and the Ames Direct-Connect Arc have increasingly been used in the current program. Despite having a unique nonvitrated heating core, the Glenn HTF has been dropped from the NASA hypersonic research programs. It is in the process of being mothballed. In the area of propulsion, the Glenn ECRL 2B has been used increasingly, given the focus of current NASA research on rotorcraft, whereas the Glenn Propulsion Simulation Laboratory cell 3 (PSL-3) has lost use under the current program structure. However, PSL-4, the other arm of the Glenn propulsion test facility, is currently needed for hypersonic research.

For additional details on NASA responses, please refer to Appendix A.

DoD Summary: DTRMC Added NTF as Mission Critical						
Sonic Speed	Location	Facility Name	RAND Survey of DoD Prior Study	Current Update**	Recent DTRMC Study	Summary of Current DoD Advocacies
Sub	Ames	12-Foot (M)	√	**		**
Sub	Ames***	NFAC	√	√	√ Critical	√
Sub	Langley	14x22-Foot	√	**	**	**
Sub	Langley	12-Foot	√ *	*		**
Sub	Langley	20-Foot Spin	√	√	√ Critical	√
Sub	Langley	LTPT				
Sub	Glenn	9x15-Foot	√	**		**
Sub	Glenn	Icing WT	√	√	√ Critical	√
Tran	Ames	11-Foot	√	√	√ Critical	√
Tran	Langley	NTF			√ Critical	√ Added
Tran	Langley	16-Foot TT	√	Closed		—
Tran	Langley	TDT	√	√	√ Critical	√
Tran	Glenn	8x6-Foot	√	**	**	**
Super	Ames	9x7-Foot UPWT	√	**	**	**
Super	Langley	4-Foot UPWT	√	**		**
Super	Glenn	10x10-Foot	√	**	**	**

* Some usage exists due to very low costs, but technical capabilities are inferior and alternatives exist
 ** Needs that the DoD did not rank as “critical” for meeting its mission
RAND

(M) Mothballed by start of current study
 *** NASA owned; USAF operated

This slide summarizes the results of our examination of DoD needs for the subsonic (Sub), transonic (Tran), and supersonic (Super) speed regimes at the NASA Ames, Glenn, and Langley research centers. Noncritical facilities with some identified potential uses are now identified with double asterisks (**) to help differentiate them from those that rise to the level of being mission-critical to the DoD.

Since our prior study, the Langley NTF is now considered a critical facility by the DoD. DTRMC noted that the DoD has used the NTF in the past for science and technology (S&T) testing of high-lift aerodynamics. The DoD has also used the NTF to support UAV concepts. The Joint Strike Fighter (JSF) program has tentative plans for use of the NTF. The NTF is vital to determining scaling effects for transport aircraft, bombers, and other long-range vehicles and to calibrate modeling and simulation (M&S) tools using physical testing under high R_n . If the NTF were not available, the only alternative wind tunnel for testing at matching high R_n would be the smaller European Transonic Wind (ETW) Tunnel in Köln, Germany.

Interestingly, our survey discussions at the DoD did not reveal any advocacy for the Langley NTF on strategic grounds, but the DTRMC study that involved the Office of the Secretary of Defense (OSD) and senior principals in the services did. We believe that the DoD's advocacy is technically valid and reflects the NTF's uniqueness as a high- R_n transonic facility and its importance despite the tentativeness of current plans. The NTF should be desired and requested by researchers and developers alike if development risks (both technical and financial) for advanced aerodynamic technology concepts are to be minimized (see the discussion in Antón et al., 2004b).

Our own survey update did not reveal any additional changes besides the fact that the Langley 16-Foot Transonic Tunnel has been closed (as recommended in the prior study); also, the Ames 12-Foot High Reynolds Number facility has been mothballed since the prior study, despite being a one-of-a-kind facility in the subsonic high-Rn speed regime.

DoD Summary: Three Additional Hypersonic Propulsion Tunnels Might Be Useful (Yet Not Critical) for the DoD

Sonic Speed/ Propulsion	Location	Facility Name	RAND Survey of DoD		Recent DTRMC Study	Summary of Current DoD Advocacies
			Prior Study	Current Update**		
Hyper	Langley	20-Inch CF4	✓	**		**
Hyper	Langley	20-Inch Air	✓	**		**
Hyper	Langley	31-Inch Air	✓	**		**
Hyper-Prop	Langley	8-Foot HTT	✓	✓	✓ Critical	✓
Hyper-Prop	Langley	Arc-Heated Scramjet			*,**	*,** new
Hyper-Prop	Langley	Combustion Heated Scramjet			*,**	*,** new
Hyper-Prop	Langley	Direct-Connect SS Combustion				
Hyper-Prop	Langley	15-Inch M6 HTT				
Hyper-Prop	Ames	Direct-Connect Arc (M)	✓	**		**
Hyper-Prop	Ames	16-Inch Shock (M)	✓	**		**
Hyper-Prop	Glenn	HTF (P)			*,**	*,** new
Hyper-Prop	NASA***	HYPULSE	✓	**		**
Hyper-Prop	Glenn	PSL-4	✓	**	**	**
Prop	Glenn	PSL-3	✓	**	**	**
Prop	Glenn	ECRL 2b	✓	**		**

* No current planned use, but recognized uniqueness
 ** Needs that the DoD did not rank as "critical" for meeting its mission
 (M) Mothballed by start of current study
 (P) Mothball preservation started during current study
 *** NASA owned; GASL operated

RAND

This slide summarizes the results from our examination of DoD needs for NASA's hypersonic wind tunnels (Hyper), hypersonic propulsion-integration facilities (Hyper-Prop), and the direct-connect propulsion test facilities (Prop) at the NASA Ames, Glenn, and Langley research centers. Only one of these facilities, the Langley 8-Foot High-Temperature Tunnel, was deemed mission-critical by the DoD, but other potential uses may ensue from the DoD if the facilities remain available. These include some newly identified potential uses for the Langley Arc-Heated Scramjet, the Langley Combustion Heated Scramjet, and the Glenn Hypersonic Tunnel Facility (HTF). The uniqueness of the Glenn HTF was noted and potential uses postulated, although it is not mission-critical to the DoD. Note that the Glenn HTF is being mothballed to preserve this unique capability in the event that vitiation becomes an issue in hypersonic propulsion testing.

For additional details, please refer to Appendix A.

Industry Advocacy (Defense and Commercial) for Facilities Has Not Changed Since Last RAND Survey Except for LTPT

Sonic Speed	Location	Facility	Prior Study	Current Industry Advocacies
Sub	Ames	12-Foot (M)	✓	(Mothballed)
Sub	Ames***	NFAC	✓	✓
Sub	Langley	14x22-Foot	✓	✓
Sub	Langley	12-Foot		
Sub	Langley	20-Foot Spin	✓	✓
Sub	Langley	LTPT	✓	Dropped
Sub	Glenn	9x15 Foot	✓	✓
Sub	Glenn	Icing WT	✓	✓
Tran	Ames	11-Foot	✓	✓
Tran	Langley	NTF	✓	✓
Tran	Langley	16TT (closed)	✓	—
Tran	Langley	TDT	✓	✓
Tran	Glenn	8x6-Foot	✓	✓
Super	Ames	9x7-Foot UPWT	✓	✓
Super	Langley	4-Foot UPWT	✓	✓
Super	Glenn	10x10-Foot	✓	✓

RAND

(M) Mothballed by start of current study
 *** NASA owned; USAF operated

This slide summarizes the results from our examination of industry needs for the subsonic (Sub), transonic (Tran), and supersonic (Super) speed regimes at the NASA Ames, Glenn, and Langley research centers. Industry responses since the last survey did not change, except for the loss of strong need for the Langley Low-Turbulence Pressure Tunnel. The Langley LTPT is a unique facility that provides flight-Rn testing capability for two-dimensional airfoils and a low-turbulence environment for laminar flow control (LFC) and transition studies and the testing of low-drag airfoils. The LTPT is a unique capability for rotorcraft testing and is complementary to the Langley 0.3-Meter Transonic Cryogenic Tunnel used for testing two-dimensional (2D) airfoil sections and other models at high Reynolds numbers. (The 0.3-Meter is not listed here because its size did not meet our study criteria.) Together, these facilities can test airfoils over the full range of lift, Reynolds, and Mach numbers. However, NASA indicated that a significant amount of investment is required to upgrade the LTPT facility. Boeing, its last advocate, has small, intermittent needs for 2D testing and, therefore, suggested developing an alternative 2D capability in the NTF as a way to consolidate the capabilities.

For additional details on industry responses, please refer to Appendix A.

Industry Advocacy (Defense and Commercial) Has Not Changed for the Hypersonic and Propulsion Cells

Sonic Speed/ Propulsion	Location	Facility	Past Study	Current Industry Advocacies
Hyper	Langley	20-Inch CF4	✓	✓
Hyper	Langley	20-Inch Air	✓	✓
Hyper	Langley	31-Inch Air	✓	✓
Hyper-Prop	Langley	8-Foot HTT	✓	✓
Hyper-Prop	Langley	Arc-Heated Scramjet	✓	✓
Hyper-Prop	Langley	Combustion Heated Scramjet	✓	✓
Hyper-Prop	Langley	Direct-Connect SS Combustion		
Hyper-Prop	Langley	15-Inch M6 HTT		
Hyper-Prop	Ames	Direct-Connect Arc (M)	✓	✓
Hyper-Prop	Ames	16-Inch Shock (M)		
Hyper-Prop	Glenn	HTF (P)	✓	✓
Hyper-Prop	GASL***	HYPULSE	✓	✓
Hyper-Prop	Glenn	PSL-4	✓	✓
Prop	Glenn	PSL-3	✓	✓
Prop	Glenn	ECRL 2b	✓	✓

(M) Mothballed by start of current study

(P) Mothball preservation started during current study

*** NASA owned; GASL operated

RAND

This slide summarizes the results from our examination of industry needs for NASA's hypersonic wind tunnels (Hyper), hypersonic propulsion-integration facilities (Hyper-Prop), and the direct-connect propulsion test facilities (Prop) at the NASA Ames, Glenn, and Langley research centers. Overall, no changes were identified by industry for the hypersonic and propulsion facilities.

Across NASA, the DoD, and Industry, Only LTPT Has Lost Advocacy									Overall Advocacy Summary
Sonic Speed	Location	Facility	NASA Past	NASA Current	DoD Past	DoD Current	Industry Past	Industry Current	
Sub	Ames	12-Foot (M)			√	Mothballed	√	√	Weak: mothballed √
Sub	Ames***	NFAC	√	√	√	√ Critical	√	√	
Sub	Langley	14x22-Foot	√	√	√	**	√	√	
Sub	Langley	12-Foot Lab	√ *	√ *	√ *	√ *,**			√ *
Sub	Langley	20-Foot Spin		√	√	√ Critical	√	√	Dropped √
Sub	Langley	LTPT	√				√		
Sub	Glenn	9x15-Foot	√	√	√	**	√	√	
Sub	Glenn	Icing WT	√	√	√	√ Critical	√	√	
Tran	Ames	11-Foot		√	√	√ Critical	√	√	
Tran	Langley	NTF	√	√		√ Critical	√	√	√
Tran	Langley	16TT (closed)	√		√	—	√	—	—
Tran	Langley	TDT	√	√	√	√ Critical	√	√	√
Tran	Glenn	8x6-Foot	√	√	√	**	√	√	√
Super	Ames	9x7-Foot UPWT		√	√	**	√	√	√
Super	Langley	4-Foot UPWT	√	√	√	**	√	√	√
Super	Glenn	10x10-Foot	√	√	√	**	√	√	√

RAND * Some usage exists due to very low costs, but technical capabilities are inferior and alternatives exist
 ** Needs that the DoD did not rank as "critical" for meeting its mission
 (M) Mothballed by start of current study
 *** NASA owned; USAF operated

This slide summarizes the results from our examination of all NASA, DoD, and industry testing needs for the subsonic (Sub), transonic (Tran), and supersonic (Super) speed regimes at the NASA Ames, Glenn, and Langley research centers. When we consider all three user communities, only the Langley LTPT has lost advocacy.

Continued Advocacy for All But One Hypersonic Cells, and Now Weak Advocacy for a Second Cell

Sonic Speed/ Propulsion	Location	Facility	NASA Past	NASA Current	DoD Past	DoD Current	Industry Past	Industry Current	Overall Advocacy Summary
Hyper	Langley	20-Inch CF4	✓	✓	✓	**	✓	✓	✓
Hyper	Langley	20-Inch Air	✓	✓	✓	**	✓	✓	✓
Hyper	Langley	31-Inch Air	✓	✓	✓	**	✓	✓	✓
Hyper-Prop	Langley	8-Foot HTT	✓	✓	✓	✓ Critical	✓	✓	✓
Hyper-Prop	Langley	Arc-Heated Scramjet		✓		**	✓	✓	✓
Hyper-Prop	Langley	Combustion Heated Scramjet		✓		**	✓	✓	✓
Hyper-Prop	Langley	Direct-Connect SS Combustion		✓					✓
Hyper-Prop	Langley	15-Inch M6 HTT							None
Hyper-Prop	Ames	Direct-Connect Arc (M)		✓	✓	**	✓	✓	✓
Hyper-Prop	Ames	16-Inch Shock (M)			✓	**			Weak
Hyper-Prop	Glenn	HTF (P)	✓			**	✓	✓	✓
Hyper-Prop	GASL***	HYPULSE			✓	**	✓	✓	✓
Hyper-Prop	Glenn	PSL-4	✓	✓	✓	**	✓	✓	✓
Prop	Glenn	PSL-3	✓		✓	**	✓	✓	✓
Prop	Glenn	ECRL 2b		✓	✓	**	✓	✓	✓

RAND ** Needs that the DoD did not rank as "critical" for meeting its mission

(M) Mothballed by start of current study
(P) Mothball preservation started during current study
*** NASA owned; GASL operated

This slide summarizes the results from our examination of all NASA, DoD, and industry testing needs for NASA's hypersonic wind tunnels (Hyper), hypersonic propulsion-integration facilities (Hyper-Prop), and the direct-connect propulsion test facilities (Prop) at the NASA Ames, Glenn, and Langley research centers. NASA needs and DoD potential uses for hypersonic facilities have generally increased, although one Langley facility continues to have no advocacy, and the potential uses for the Ames 16-Inch Shock Tunnel has weakened in that only noncritical DoD needs were identified. The Glenn HTF is still recognized to be unique, despite its current lack of use.

We Assessed Strategic Importance Based on Advocacy Combined with Technical Issues and Uniqueness within NASA

Sonic Speed	Location	Facility	Overall Advocacy Summary	Technical Issues*	Primary NASA Facility*	Strategically Important
Sub	Ames	12-Foot (M)	Mothballed	✓	✓	✓ (M)
Sub	Ames***	NFAC	✓		✓	✓
Sub	Langley	14x22-Foot	✓		✓	✓
Sub	Langley	12-Foot Lab	Not strategic	✓		No
Sub	Langley	20-Foot Spin	✓		✓	✓
Sub	Langley	LTPT	Dropped		✓	Dropped
Sub	Glenn	9x15-Foot	✓		✓	✓
Sub	Glenn	Icing WT	✓		✓	✓
Tran	Ames	11-Foot	✓		✓	✓
Tran	Langley	NTF	✓		✓	✓
Tran	Langley	16TT (closed)	—	✓		No
Tran	Langley	TDT	✓		✓	✓
Tran	Glenn	8x6-Foot	✓		✓	✓
Super	Ames	9x7-Foot UPWT	✓		✓	✓
Super	Langley	4-Foot UPWT	✓		✓	✓
Super	Glenn	10x10-Foot	✓		✓	✓

* See Antón et al., 2004b

(M) Mothballed by start of current study
 *** NASA owned; USAF operated

RAND

We then assessed which of NASA's facilities are strategically important by combining the updated advocacy information with our knowledge of facility technical issues and uniqueness within NASA from our prior study (Antón et al., 2004b). This slide summarizes the results for the subsonic (Sub), transonic (Tran), and supersonic (Super) speed regimes at the NASA Ames, Glenn, and Langley research centers. Technical issues reflect serious deficiencies identified in our assessment and in the detailed advocacy responses summarized in Antón et al. (2004b, pp. 31–32). Primary NASA facilities were identified in our prior study in a map of NASA's WT/PT facilities against the types of facilities needed by the nation (Antón et al., 2004b, pp. 24–27).

We dropped the Langley LTPT from the list of strategically important facilities in addition to the two other facilities we excluded from the list in our prior study (Antón et al., 2004a, 2004b). The LTPT's situation is described on a subsequent slide.

Continued Advocacy for All But One Hypersonic Cells, and Now Weak Advocacy for a Second Cell

Sonic Speed/ Propulsion	Location	Facility	Overall Advocacy Summary	Technical Issues*	Primary NASA Facility*	Strategically Important
Hyper	Langley	20-Inch CF4	✓		✓	✓
Hyper	Langley	20-Inch Air	✓		✓	✓
Hyper	Langley	31-Inch Air	✓		✓	✓
Hyper-Prop	Langley	8-Foot HTT	✓		✓	✓
Hyper-Prop	Langley	Arc-Heated Scramjet	✓		✓	✓
Hyper-Prop	Langley	Combustion Heated Scramjet	✓		✓	✓
Hyper-Prop	Langley	Direct-Connect SS Combustion	✓			✓
Hyper-Prop	Langley	15-Inch M6 HTT	No			No
Hyper-Prop	Ames	Direct-Connect Arc (M)	✓	✓? (M)	✓	✓
Hyper-Prop	Ames	16-Inch Shock (M)	Weak	✓? (M)	✓	Weak
Hyper-Prop	Glenn	HTF (P)	✓		✓	✓
Hyper-Prop	GASL***	HYPULSE	✓		✓	✓
Prop	Glenn	PSL-3	✓		✓	✓
Prop	Glenn	PSL-4	✓		✓	✓
Prop	Glenn	ECRL 2b	✓		✓	✓

* See Antón et al., 2004b

(M)

Mothballed by start of current study

(P)

Mothball preservation started during current study

NASA owned; GASL operated

RAND

This slide summarizes the results of our assessment of strategic importance for NASA's hypersonic wind tunnels (Hyper), hypersonic propulsion-integration facilities (Hyper-Prop), and the direct-connect propulsion test facilities (Prop) at the NASA Ames, Glenn, and Langley research centers. Technical issues reflect serious deficiencies identified in our assessment and in the detailed advocacy responses summarized in Antón et al. (2004b, pp. 31–32). Primary NASA facilities were identified in our prior study in a map of NASA's WT/PT facilities against the types of facilities needed by the nation (Antón et al., 2004b, pp. 24–27).

The Langley 15-Inch Mach 6 High-Temperature Tunnel has dropped from the list of strategically important facilities (see discussion on next slide).

Thus Two Additional Facilities Lack Strategic-Level Support

- **Advocacy for LTPT has waned**
 - It is a unique capability for rotorcraft testing
 - Complimentary to 0.3m Cryogenic tunnel, airfoils can be tested over the full range of lift, R_n , and Mach numbers
 - Considerable investment is required to upgrade the facility
 - Industry suggestion to develop a 2D capability elsewhere (e.g., in NTF) as a way to consolidate the capabilities
 - Unclear how this need would compare to other investment needs being considered by NASA's ATP
- **One component of the Langley hypersonic propulsion integration suite continues to lack strategic support and thus should be removed from the strategic facilities list**
 - **Langley 15-Inch Mach 6 High-Temperature Tunnel**
 - Strategic importance of the other three facilities in the Aerothermodynamic Facilities Complex suite will prevent the elimination of any shared infrastructure

RAND

Overall, there have been few changes since the previous study. Boeing and NASA discontinued advocacy for the Langley LTPT, despite the fact that it has unique capabilities for rotorcraft testing. Use has been very low, and the facility is aging. Significant investment is required to upgrade the LTPT. As discussed, Boeing has suggested developing a 2D capability in the NTF as a way to consolidate the capabilities and maintain a 2D domestic capability.

One component of the Langley hypersonic propulsion integration suite continues to lack strategic support and, thus, should be removed from the strategic facilities list: the Langley 15-Inch Mach 6 High-Temperature Tunnel. However, because of shared infrastructure and support for the other three facilities in the Aerothermodynamic Facilities Complex suite and the overall Langley hypersonic suite of facilities, closing this facility will likely not engender large savings.

Mothballing the Ames 12-Foot Reflects Lack of Use Yet Will Delay Loss of the Last U.S. High-Rn Subsonic Capability

- **Ames 12-Foot Pressure WT is the only large general-purpose high-Rn subsonic capability in the United States**
 - High-Rn test capability is important for understanding flight performance (e.g., at takeoff and landing)
 - Lack of such would impact many new vehicles and research
- **Unavailability during reconstruction (1988–95) forced users overseas, and technical factors have kept them there**
 - Boeing continues to maintain a strategic relationship with the 5-Metre QinetiQ tunnel in the UK
 - Other users are going overseas when security is not at issue
- **Overseas usage is driving NASA to mothball the Ames 12-Foot**
 - Preserves equipment in case of foreign access or security problems
 - Closure driving other users overseas as well (e.g., to ONERA F1)
- **The United States could consider strategic reliance on foreign facilities if security and access concerns were addressed**

RAND

The reality of low use is driving two facilities to be mothballed to preserve their capabilities for future use.

First, let us consider the Ames 12-Foot Pressure WT. The Ames 12-Foot is the only large general-purpose high-Rn subsonic WT in the United States (since the NFAC is not generally suitable for most vehicle types requiring high Rn). This capability is important for the development of low-speed configurations (e.g., during takeoff and landing).

The Ames 12-Foot had very low initial utilization since its rebuild from 1988 to 1995—and no recent use. Most government vehicle acquisition programs encourage contractors to select test capabilities based on cost and availability rather than being forced to use domestic facilities, and the QinetiQ 5M in the UK has attracted work from the 12-Foot. The extended unavailability of the 12-Foot did not help. Users were forced to seek alternatives, and they established databases and experience with the QinetiQ 5M. The decision to rebuild the 12-Foot to the specifications of the original facility did not allow the United States to take advantage of advances in testing technology and build a superior facility (see the discussion in Antón et al., 2004a, 2004b). France's ONERA (*Office National d'Études et de Recherches Aéronautiques*—the French National Office for Aerospace Studies and Research) F1 is also a possibility for some applications.

The Ames 12-Foot continues to have very limited support and advocacy from industry. The QinetiQ 5M (retained by Boeing) is either the primary or only choice for users because of its superior features and technical capabilities. A number of notable, strong critics enumerated the deficiencies of the 12-Foot—for example, some unresolved deficiencies (highlighted by the

Naval Air Systems Command [NAVAIR]) were not addressed by Ames center management because of prior lack of support for WTs.

The continued flow of testing to foreign facilities has driven NASA to mothball the Ames 12-Foot. This preserves the hardware in the country's sole high-Rn facility in the event that it is needed in, say, the next five to ten years. The loss of workforce skills is not as big a loss as it might be, in that there was little testing experience with the 12-Foot after the rebuild.

If other high-Rn transonic and supersonic tunnels can be modified to run at low Mach numbers, then a more permanent decision concerning the 12-Foot would be apparent. Likewise, the United States could consider examining a strategic reliance on foreign facilities, but it would need to recognize the security and access risks and should then try to address them (see the discussion in Antón et al., 2004a, 2004b).

Glenn HTF Has a Unique Non-Vitiated Capability, But Lack of Planned Utilization Has Forced It into Mothball

- **Glenn Hypersonic Tunnel Facility (HTF) is strategically important from the perspective of its unique, non-vitiated heating capability**
 - Air-breathing hypersonic propulsion is still in research stages
 - Challenges may be due to the unnatural presence of facility heating combustion byproducts in the test cells of vitiated facilities
 - Preserving HTF is a hedge in the event that vitiation turns out to be a real roadblock in hypersonic propulsion research
- **Glenn HTF has no current or planned usage on current programs**
 - Not included in NASA's current hypersonics research program
 - No current industry use

RAND

The other NASA facility being put into mothball because of a lack of recent use is the Glenn Hypersonic Tunnel Facility.

The Glenn HTF is strategically important from the perspective of its unique, nonvitiated heating capability. Air-breathing hypersonic propulsion is still in its research stage. One challenge in this research may be the unrealistic presence of heating combustion by-products in the test cells of vitiated facilities. The only other nonvitiated facility is the smaller, 11-Inch Langley Arc-Heated Scramjet Test Facility (the Glenn HTF has a 42-inch exit diameter nozzle).

Despite this fact, hypersonic testing at the Glenn HTF has not occurred for years. The facility has been dropped from NASA's hypersonic research programs and is not in any current industry research program. These testing plans reflect the current thinking of those in the hypersonic community and their preference for other facilities that offer different technical advantages. Thus, the Glenn HTF is in a weaker strategic position than that of other NASA WT/PT facilities, and putting the Glenn HTF into mothball is a hedge in the event that vitiation turns out to be a real roadblock in hypersonic propulsion research.

Additional discussion on hypersonic propulsion testing and these facilities can be found in Antón et al. (2004b).

Technical Capabilities Generally Drive User's Choice of Facilities for a Given Test

- **NASA's WT/PT capabilities operate in a national and international marketplace of test facilities**
 - **Decision factors include technical trade-offs, prices, workforce, availability, and security**
- **Our survey responses generally indicated that users consider non-NASA facilities primarily for technical capability factors if prices are reasonable**
 - **NASA ATP is supplementing user fees to keep costs in line with estimated market competitive prices**
 - **We found no systematic concerns about NASA facility availability, security, or customer support issues**

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One might ask what factors influence a user's selection of a facility for a given test and whether there are systemic issues with NASA's facilities that appear to drive users away.

NASA's WT/PT capabilities operate in a national and international marketplace of test facilities. In other words, NASA, DoD, industry, and international facilities all serve U.S. strategic testing needs based on their capabilities and other factors. Decision factors include technical trade-offs, prices, workforce, availability, and security.

Our survey responses generally indicated that, when users go to non-NASA facilities, it is primarily for technical capability factors if prices are reasonable. NASA ATP is supplementing user fees to keep costs in line with estimated market competitive prices, so technical advantages and state-of-the-art offerings remain critical to decisions about use. We found no systematic concerns about NASA facility availability, security, or customer support issues.

Although National Consolidation Was a Topic Beyond the Scope of Our Studies, Candidates from a Technical Perspective Were Identified in the Prior Study

Candidates for collaboration and reliance on DoD facilities include the following facilities:

(Source: Antón et al., 2004a, 2004b)

- **Ames 11-Foot Transonic High-Rn WT**
 - AEDC 16-Foot Transonic WT (16T)
- **Ames 12-Foot High-Rn Subsonic Pressure WT**
 - If AEDC 16-Foot Transonic or Supersonic WTs (16T or 16S) could provide efficient high-Rn subsonic testing at a reasonable cost
- **Glenn 8x6-Foot Propulsion Transonic WT**
 - AEDC 16-Foot Transonic Propulsion WT (16T)
- **Glenn 10x10-Foot Propulsion Supersonic WT**
 - AEDC 16-Foot Supersonic Propulsion WT (16S)
- **Glenn Propulsion Simulation Laboratory (PSL-3 and PSL-4)**
 - AEDC C, J, and T cells.

Consolidation and reliance issues require further analysis

- *What new costs will be incurred, and how do they compare to savings?*
- *Can NASA and DoD resolve access and prioritization issues?*
- *Are the technical differences worth any added costs to retain these facilities?*

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Although national consolidation was a topic beyond the scope of this study, candidates for collaboration and reliance on DoD facilities include those listed in our prior study (Antón et al., 2004a, 2004b).

Some of these NASA facilities provide capabilities that could be met by some (often larger and more expensive to build and operate) test facilities maintained by the DoD at AEDC or by foreign facilities. Whether it is prudent to close selected NASA facilities and rely on these other facilities requires further analysis.

It is unknown whether further facility consolidation across NASA and AEDC would provide a net government savings. Sites with multiple facilities have large, common infrastructures with fixed recurring costs that are not reduced when a subset of the site's facilities is closed; closures merely shift these fixed infrastructure costs to the remaining facilities. Also, gross savings from eliminating a facility's operating budget must be weighed against increased costs in time, travel, shipping, higher testing costs, and lost opportunity to research programs to test at nonlocal facilities.¹ There is also the risk that unforeseen future programs may need facilities whose unique capabilities appear less important today. Cost data to understand the financial implications of these testing trade-offs were not available during this study, primarily

¹ It is unclear how strong a requirement it is that a tunnel be colocated with a research community. Convenience is certainly a factor voiced by those who advocate use of local facilities, and transportation costs can be significant. However, distant facilities may offer better capabilities, and some advances in remote data monitoring have reduced some needs to send a full test crew to distant sites. Industry users are accustomed to testing at nonlocal sites because of necessity. A full analysis would be needed for each candidate set of tunnels to understand how the costs compare with the benefits.

because NASA was still implementing full-cost accounting of its operations. Other data, such as alternative facility testing quotes and costs to programs for nonlocal testing, would require additional, in-depth analysis across the facility alternatives and NASA programs.

Nevertheless, there are possible consolidation opportunities here, especially in the latter four sets. The Ames 11-Foot is a less likely candidate because it is was rated as critical to the DoD for additional capacity and as a backup to AEDC 16 (AT&L, 2007). The Ames 12-Foot is already mothballed, so developing an alternative capability at the AEDC would be very desirable from a national capability perspective.² The transonic and supersonic propulsion test facilities at NASA Glenn have some technical differences from the AEDC facilities, but they also had good utilization when we examined testing levels in our study. The propulsion cells (PSL-3 and PSL-4) are much more similar to those at AEDC and could be examined to determine the amount of capacity the nation needs.³

Beyond cost considerations, reliance on facilities outside NASA requires clarifying their availability and examining needed resident expertise. Currently, DoD programs have first priority at DoD facilities, potentially restricting NASA or industry access for extended periods. NASA and the DoD would need to discuss such access issues and determine whether research programs could forgo access for such periods or whether surge capabilities are an option (e.g., by adding extra shifts). Also, tests at NASA's Glenn and Langley facilities benefit from the resident aeronautics expertise at these centers, so an examination should be made to understand how the lack of such on-site research expertise at the AEDC would affect the quality of research and development (R&D) performed at AEDC facilities.

The consolidation and reliance issues are not straightforward. In many cases, AEDC facilities provide more capabilities than are needed, and they are more expensive to operate for a given test. In other cases, technical differences between the facilities may preclude trade-offs (e.g., open-loop propulsion exhausting at the Glenn propulsion WTs compared with closed-loop scoop exhaust recovery at AEDC facilities).

² Two unpublished options hypothesized by AEDC with some preliminary internal investigations were to upgrade AEDC 16T or 16S to provide high-Rn testing at subsonic speeds. (AEDC 16T can already operate down to Mach 0.2, but the Rn in AEDC 16T drops in the subsonic range.) It is unclear what the cost would be and whether it would be cheaper than, say, building a new facility from scratch. Given the current high demand for AEDC 16T, it might not be viable to take it offline for a long time for such a significant modification. This may have been the reason behind the consideration of modifying AEDC 16S, which is currently mothballed.

³ However, NASA is currently planning to add an icing capability to the Glenn PSL, and there are discussions about whether such a capability could be made portable so that AEDC cells could use it as well. The final resolution of these plans may yield distinct technical differences or new commonalities between AEDC and NASA Glenn cells.

Certain Strategically Important Facilities Offer Capabilities That Cannot Be Met Elsewhere in the Country Regardless of Cost, Access, or Improvements					
	Subsonic	Transonic	Supersonic	Hypersonic and Propulsion Integration	Direct Connect
Ames	• 12-Foot Pressure (M) • NFAC*	• 11-Foot	• 9x7-Foot	• 16-Inch Shock (M) • Direct Connect (M)	
Glenn	• 9x15-Foot • Icing WT	• 8x6-Foot	• 10x10-Foot	• PSL-4 • HTF (P)	• PSL-3 • ECRL 2b
Langley	• 14x22-Foot • 12-Foot lab • LTPT • 20-Foot Spin	• NTF • TDT • 16TT	• 4-Foot Unitary	• 8-Foot HTT • 20-Inch Mach 6 Air • 20-Inch Mach 6 CF4 • 31-Inch Mach 10 Air • 15-Inch Mach 6 HTT • Arc-Heated Scramjet • Combustion Scramjet • Supersonic Combustion • HYPULSE**	

 Strategically important and cannot be met by any other U.S. facility regardless of cost, moderate improvements, or access concerns
 Strategically important
 Not strategically important

RAND (Source: Antón, 2005a)

(M) Mothballed by start of current study
 (P) Mothball preservation started during current study
 * NASA owned; USAF operated
 ** NASA owned; GASL operated

Another way to prioritize facilities is to identify which ones offer capabilities that cannot be met elsewhere in the country, regardless of cost, access, or improvements. This slide identifies (in circles and boldface) the facilities that meet these stricter criteria based on the analysis by Antón (2005a). The remaining facilities that do not meet these stricter criteria yet are still deemed strategically important using the less restrictive criteria used earlier are shown in white. Facilities that lack strategic support are shaded gray.

...But Sole Focus Only on Domestic Uniqueness Can Incur Significant Cost and Cause New Strategic Issues

- In using these criteria to form a list of those facilities especially detrimental to close, it is important to note the following:
 1. If the facilities that did not make this list are closed, then the testing costs to go to other U.S. facilities may be much higher, and relying on them may, in the long run, cost this country more money, especially in future research programs that would probably have to spend more on testing in alternative facilities than they would otherwise.
 2. Higher testing costs at alternative U.S. facilities may drive users to cheaper foreign facilities, reducing the amount of domestic facility business and incurring risks related to foreign facility testing.
 3. Each test facility is unique in some way, so this list does not consider all technical differences.
 4. The facilities most detrimental to close would affect any strategic national need from all sectors—NASA research, civil aviation, military, and space—not just NASA research needs.

RAND

(Source: Antón, 2005a)

In using the criteria on the prior slide to form a list of those facilities especially detrimental to close, it is important to note the following.

If the facilities that did not make this list are closed, then the testing costs to use other U.S. facilities may be much higher; thus, relying on those other facilities *may, in the long run, cost this country more money*, especially in future research programs that would probably incur more costs for testing in alternative facilities than they would otherwise. In many cases, alternative facilities are more sophisticated and have more capabilities than needed (e.g., they are larger or have additional technical features that cost more).

Higher testing costs at alternative U.S. facilities *may drive users to cheaper foreign facilities*, reducing the amount of domestic facility business and incurring risks (discussed later) related to foreign facility testing.

Each test facility is unique in some way, so this list *does not consider all technical differences*.

The facilities most detrimental to close would affect any strategic national need from all sectors—NASA research, civil aviation, military, and space—not just NASA research needs (Antón, 2005a).

Thus, although prioritization is useful and important, significant issues arise when considering a reduced list of capabilities.

Foreign Reliance Might Be a Plausible Future Step, but Security Concerns Would Need to Be Addressed

“In search of lower costs and modern wind tunnel technology, U.S. customers typically conduct 25 percent of their wind tunnel development at European facilities.”

“Without tight controls on access and data management, critical technology is at significant risk for compromise at most, if not all, of the listed facilities or in transit to and from them. Despite contractual security specifications, the designs or data deployed to these sites is in a virtual sea of potential collectors – whether representing national, commercial or private interests.”

[Emphasis added]

(SOURCE: Counter-Intelligence Field Activity, 2004)

RAND

Foreign reliance might be a plausible future step, but security concerns would need to be addressed. The unclassified excerpts from a DoD Counter-Intelligence Field Activity (CIFA) report confirm, shown on the slide, that there is some movement to European facilities for cost and technical reasons but that there are security concerns with these tests.

Sometimes costs in Europe are lower because their facilities' capabilities more closely match users' needs (e.g., in terms of size or other technical capability). Also, under NASA's former policy of full cost recovery, NASA's test prices reflected the user's share of the year's operational expenses, not market prices. We expect the shared support by NASA ATP to help address this.

Relying on foreign facilities can add security concerns, in addition to concerns relating to cost, availability, and technical differences. The DoD CIFA report found that critical technology is at a significant risk of compromise at most, if not all, facilities they studied (CIFA, 2004). Thus, there are also nonmonetary costs to consider when trying to use foreign capabilities in lieu of retaining domestic facilities.

In Summary, the Nation's Need for NASA Capabilities Has Not Changed Significantly Since Our Prior Study

27 of the 31 tunnels we originally studied are still strategically important for serving national strategic needs

- **LTPT has very weak support and could be closed**
 - Consider developing a 2D capability (say, in the NTF)
 - Significant investment is required to keep it in operational status
 - Consider mothballing in the near term if not prohibitively expensive
- **Langley 15-Inch Mach 6 High-Temperature Tunnel continues to have no advocacy and could be closed**
 - Strategic importance of the other three facilities in the Aerothermodynamic Facilities Complex suite will prevent the elimination of any shared infrastructure
- **Two others from our last study continue to lack strategic importance**

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In summary, the nation's needs for NASA's capabilities have not changed significantly since the prior study. Of the 31 facilities originally studied, 27 are still considered strategically important. The Langley LTPT has lost advocacy both within NASA and with Boeing (the only industrial advocate, which has suggested consolidation of the tunnel's capabilities in the NTF at Langley).

One component of the Langley hypersonic propulsion integration suite continues to lack strategic support and, thus, should be removed from the strategic facilities list: the Langley 15-Inch Mach 6 High-Temperature Tunnel. However, because of support for the other facilities in the Aerothermodynamic Facilities Complex suite, it is hard to reap savings from closing this facility.

The Two Mothballings Make Sense to Preserve As Much of These Strategic Facilities As We Can, but Additional Resources Might Support Academic Testing

- Mothballing the Ames 12-Foot High-Rn pressure tunnel has no negative impact as long as overseas security and access are not issues
 - Mothballing the Glenn HTF makes sense given uniqueness and no current use
 - NASA is trying to preserve more workforce knowledge than the last time HTF was mothballed
- Still some risk that these facilities will be lost
 - Especially from loss of workforce knowledge
 - NASA could assess alternative ideas to preserve these capabilities
 - e.g., fund periodic academic research testing in selected facilities

RAND

The two mothballings make sense to preserve as many of these strategic facilities as we can, but additional resources at ATP might support academic testing to help keep low-utilization facilities open and functioning. Mothballing the Ames 12-Foot High Reynolds number facility has no negative effect, as long as security and access to facilities overseas are not issues. Mothballing the Glenn HTF makes sense given its long period of nonuse, despite its uniqueness and its potential importance if vitiation becomes an issue in advancing hypersonic propulsion research.

There are some risks with this approach, however. When a facility is mothballed, workforce skills atrophy rapidly, and the staff may retire or leave NASA. One idea to help prevent such mothballings in the future may be to finance academic research testing at low-utilization facilities to give the facility and its staff an opportunity to maintain their skills while providing useful research opportunities in facilities that the students could not otherwise afford to use. The goal is to help make national test capabilities available to the research community while providing bridge use in a lull. Exercising this idea would require analysis of the utility of the facility in question and the research benefits that would ensue.

Outline

- **Background**
- **Wind tunnels and propulsion test facilities**
- **Simulators**
- **Conclusions**
- **Appendix A: NASA, DoD, and industry input details**
- **Appendix B: Simulator descriptions**
- **Appendix C: Technical discussion of simulation and simulators**

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The following slides discuss the strategic needs for NASA's six simulators considered in this study and then summarize our results.

We Were Also Asked About the Six Major Motion and Visualization Simulators at NASA

Motion simulators

- Long lateral-transversal simulators
 - Ames Vertical Motion Simulator (Ames VMS)
- Hexapods
 - Ames Crew-Vehicle Systems Research Facility (CVSRF)
 - Langley Cockpit Motion Facility (CMF)
 - Langley Visual Motion Simulator (Langley VMS)

Maneuvering-effect immersive visual paired simulator

- Langley Differential Maneuvering Simulator (DMS)

Area visualization team simulator

- Ames Future Flight Central (FFC)

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We were asked to look into the following six simulators: (1) the Ames Vertical Motion Simulator (VMS), (2) the Ames Crew-Vehicle Systems Research Facility (CVSRF), (3) the Langley Cockpit Motion Facility (CMF), (4) the Langley Visual Motion Simulator (VMS), (5) the Langley Differential Maneuvering Simulator (DMS), and (6) the Ames FutureFlight Central (FFC).

The Ames VMS is a major national resource, providing long lateral and transversal motion. The Ames CVSRF, Langley CMF, and VMS are research hexapod motion simulators. The Langley DMS is a matched pair of maneuvering-effect immersive visual simulators. The Ames FFC is a simulation room with surround visualization screens.

See Appendix B for additional details on these facilities.

Numerous Non-NASA Hexapod Simulators Exist, but Most Configurations Are Not Modifiable for Research

- **Different user communities use simulators (e.g., hexapods) for different objectives**
 - **Research: NASA, DoD**
 - **Product development and risk reduction: Aircraft manufacturers, DoD**
 - **Pilot training: Airlines, DoD**
- **Training, development, and risk assessment simulators usually have fixed, FAA-certified configurations and may lack access to software source code**
 - **Aircraft manufacturers typically have fixed, dedicated simulators—one for each platform**
 - **Airlines have fixed-configuration simulators for training purposes**
- **For research purposes, a simulator’s hardware or software often needs to be modified**

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Simulators have different ownership and management characteristics from those of WT/PT facilities. Simulators are relatively less expensive to acquire; thus, there are many more of them available across the nation. NASA, the DoD, and industry use simulators for a variety of reasons. NASA and the DoD use simulators for research and conceptual development. Industrial users, such as Boeing, use simulators for product development and risk reduction. Finally, commercial airlines typically use simulators for pilot training.

Although many simulators exist within industry, gaining access to them for research purposes can be difficult and expensive, since these typically are dedicated, certified facilities with fixed configurations. For example, aircraft manufacturers may have one dedicated facility for each platform, and airlines may have dedicated facilities for training purposes only.

The Combination of Capabilities at NASA's Facilities Are Generally Not Available Elsewhere

- **Usually no concern about modifying the simulator hardware or software**
- **Complete access to manufacturers' software source code**
 - **Enables embedding control algorithms in the code, testing out multiple hardware displays, joysticks, etc., on the control panel**
 - **Ability to configure the simulator to mimic multiple types of aircraft**
 - **Source code is not usually available at standard simulator installations**
- **In some cases simulators are larger and unique (e.g., Ames VMS)**
- **Research staff with significant corporate memory**
- **Independence from aircraft and airline companies can add more objectivity**
- **Therefore, NASA facilities are primary (sometimes unique) capabilities from a research perspective**

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Unlike the case with DoD and industry hexapods, the main objective of NASA hexapods is to conduct research. NASA's hexapods also are supported by a research staff who have significant corporate knowledge in adapting facilities and helping users in their tests. The research staff have access to the manufacturers' software source code, thus enabling them to embed or modify control algorithms and also test different hardware, such as joysticks, on the control panel. The displays are typically reconfigurable to multiple platforms, thereby making these simulators flexible facilities capable of addressing research issues related to different types of aircraft. Additionally, NASA's facilities and its research support staff, as part of the government infrastructure, have a degree of independence that enables them to be honest brokers to aircraft manufacturers and airline companies. Overall, the combination of these capabilities at NASA's facilities is generally not available elsewhere.

Langley and Ames Hexapods Have Somewhat Different Research Foci

- **Ames hexapod (CVSRF)**
 - **Focus: Human-machine interactions that are typically conducted in the ACFS**
 - **FAA-certified 747 simulator is not amenable to research involving multiple platforms**
- **Langley hexapods (CMF and VMS)**
 - **Focus: utility of multiple control-panel displays and testing control algorithms for human factors and control**
 - **Langley VMS to be replaced by CMF when operational**

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The hexapod simulators at NASA Langley and Ames have somewhat different research foci and, thus, somewhat different capabilities. The ACSF simulator in the Ames CVSRF focuses on human-machine interactions. The Langley CMF focuses on the utility of multiple control-panel displays and the development and testing of control algorithms, typically by embedding them in the software code provided by the manufacturer. The FAA-certified 747 simulator in the Ames CVSRF is typically not amenable to research on multiple platforms, because the certification precludes modification of the cockpit and system software.

Theoretically, the two hexapods—the Ames ACSF and the Langley CMF—represent a redundancy in capability within NASA, but there are some differences between them. In addition to hardware differences in the hexapod cabs, as noted above, the research staff at Ames focus on human-machine interactions whereas those at Langley focus on the utility of control-panel displays and control algorithms. These differences would need to be taken into consideration if NASA pursued facility consolidation by decommissioning one of the facilities. The Langley Visual Motion Simulator is also a hexapod that is being phased out and replaced by the CMF, so it is an easier target for potential consolidation.

Excluding Future Flight Central, Simulators Are Needed by NASA ARMD's Current Programs and ESMD's Strategic Needs

Simulators:	ESMD	Aviation Safety				Airspace Systems		Fundamental Aeronautics			
		Aircraft Aging and Durability	IVHM	IRAC	IIFD	ATM - Airportal	ATM - Airspace	Fixed-Wing Subsonic	Rotary-Wing Subsonic	Super-sonic	Hyper-sonic
Ames Vertical Motion Simulator (VMS)											
Ames Crew-Vehicle Systems Research Facility (CVSRF)											
Ames Future Flight Central (FFC)											
Langley Cockpit Motion Facility (CMF)											
Langley Visual Motion Simulator (VMS)*											
Langley Differential Maneuvering Simulator (DMS)**											

RAND

 Current programs needs

 Strategic needs

* Older motion facility eventually phased out when CMF is up and running

** Mothballed

This slide summarizes the results from our examination of the needs from NASA's newly restructured research programs across aeronautics and exploration systems (ARMD and ESMD, respectively) for the simulators at NASA Ames and Langley research centers. NASA's ARMD programs have needs for the Ames VMS, Ames CVSRF, and Langley CMF. ESMD provided broad strategic needs for the kind of capabilities at these facilities rather than detailed programmatic needs from their current program plans. NASA's ESMD programs expressed broad strategic needs for all facilities, excluding the Ames FFC.

Therefore, the strongest NASA needs focus on the large Ames VMS capability, as well as the leading hexapod capabilities at Ames and Langley. The need for the Langley VMS probably reflects the need for Langley's hexapod simulation capability and the fact that the Langley CMF is not yet available for operational tests.

The DoD Needs Ames VMS, Langley CMF, and Langley DMS; Industry Mostly Uses Its Own Simulators

The DoD needs

- Ames VMS is mission critical for the DoD (DTRMC study)
- Interviews with NASA Langley and USAF personnel indicated DMS is a strategically important facility for classified DoD research
- NAVAIR has shown interest in the use of simulation capabilities at the Langley Cockpit Motion Facility

Industry needs

- Aperiodic needs with no consistent user base
- Aircraft manufacturers and airlines mostly use their own, in-house facilities
 - Primarily hexapods
 - Each facility is typically dedicated to a specific platform/configuration
 - Aircraft manufacturers use simulators for product development and risk reduction prior to first flight and follow-on design iterations
 - Airlines use simulators for pilot training

RAND

The DoD uses the Ames VMS, Langley CMF, and Langley DMS. The DTRMC study identified Ames VMS as a mission-critical facility (AT&L, 2007). Interviews with NASA Langley and USAF personnel indicated that the mothballed Langley DMS is a strategically important facility for classified DoD research. When the facility is needed, DoD users pay to have it brought out of mothball and put back into mothball when testing is completed. The Naval Air Systems Command indicated an interest in using simulation capabilities at the CMF at Langley. Army researchers at Ames have shown some interest in using the Ames FFC, but that interest has not materialized into actual tests.

Industry, however, has aperiodic needs for NASA's simulators, with no consistent user base. Industry has many dedicated in-house simulation capabilities that are platform-specific and used for product development and pilot training.

Ames Future Flight Central Is Really a Laboratory and Is Not a Strategically Important Capability

- **FFC is a laboratory**
 - Replacement costs are relatively low: approximately \$10–15 million
 - Could be rebuilt relatively quickly if needed (order of years, not decades)
 - Primarily a computer visualization and processing laboratory whose components will obsolesce quickly
 - Maintenance is minimal (mostly computers and software)
- **Currently unused, and needs are very weak**
 - We identified some interest by airports and the U.S. Army
 - Geared towards commercial product development
 - Might be useful for developing protocols in new problem spaces
 - Army researchers at Ames suggested the possibility of using this facility to develop protocols for manned and unmanned systems in a wartime environment such as in Iraq
 - No NASA or FAA program needs
- **Therefore, FFC is not strategically important and could be left to survive on its own**

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The Ames FFC is really a laboratory rather than a significant, strategically important national test capability. Replacement costs are relatively low—approximately \$10 million in then-year dollars (Mewhinney, 1999), and a similar capability could be built relatively quickly if needed (on the order of years, not decades) and would also be able to exploit the improved computational and display technologies available at construction time.

The Ames FFC simulates a control-tower room environment with an immersive, 360-degree visual display of traffic in and around a simulated airport. The 360-degree visual displays operate in real time, using resident or external control of the entities in the simulation. Typical research areas for this facility include addressing runway incursion, air-traffic management, control-tower protocols under different air-traffic scenarios, and human-factors research under these conditions. It is not surprising that airport managers have shown some interest in this facility, but they have yet to fund tests there. Army researchers resident at Ames have also shown some interest, suggesting the possibility of using this facility to develop protocols for manned and unmanned systems in a wartime environment, such as Iraq. NASA has no program needs for this facility, and the FAA has withdrawn support for it.

As a research laboratory that does not have strategic national needs, the Ames FFC could be left to survive on its own through continued marketing of its capabilities to potential users, such as airport engineers. Maintenance issues are minimal, because it is a computer visual simulation facility with no physical simulation or other hardware components. However, obsolescence issues will arise with processors and displays as computer visualization technology continues its rapid pace of development.

Ames CVSRF and Langley CMF Hexapods Could Be Studied in the Future for Possible Consolidation If Utilization Became Consistently Low

- We do not have the utilization data to indicate if consolidation is warranted
 - Program delays if the other facility does not have enough unused capacity
- Closures can immediately reduce contractor labor and variable center costs, but additional costs might be incurred
 - Potentially higher costs for travel, mothballing, or demolition
- Civil servant staff are not necessarily reduced when a single facility is closed at a center
 - Civil servant regulations make it difficult to quickly reduce civil servant staff
- Langley CMF is new but still undergoing safety tests with no firm IOC date
- Long-range consolidation to one center might be a future management goal to consider
 - Any shared infrastructure costs would require closing all dependent facilities
 - Ames still has VMS, and Langley has DMS, so hard to consolidate all NASA simulators to a single center until one of these becomes obsolete
 - Ames VMS is much more heavily used and was rated critical by DoD
 - Somewhat specialized workforce skills in each location would complement each other but require relocation if consolidated

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As for prioritizing facilities and trying to identify redundancies, the Ames CVSRF and Langley CMF could be studied in the future for possible consolidation if utilization becomes insufficient to keep both facilities gainfully employed. Both facilities provide similar motion behavior because of their hexapod designs.

Closing one of these facilities might save money, but certain issues would need to be addressed. There are also resident simulation research efforts at both Ames and Langley, and a closure of one of these facilities would incur travel costs to the other facility, unless these research efforts were also consolidated in a single center. Complete consolidation at one center would be difficult because Ames still has VMS, which will remain critical for NASA and DoD testing. Langley has DMS, which, although mothballed, has yet to be abandoned by the DoD and has some potential need by the NASA ESMD. Finally, consolidation of the somewhat specialized workforce skills from each location would complement the other but may incur relocation expenses.

Summary: The United States Needs Many of NASA's Simulators—Except Two

4 of 6 simulators are strategically important, but 2 are not

- Motion capability in simulators is a risk-reduction tool that attempts to simulate real flight conditions and response
- Ames FFC is a small laboratory rather than a strategically important test capability
 - Has no current or projected NASA or FAA needs
 - Capabilities are of interest primarily to airport authorities to research air traffic issues and to some Army researchers
 - Mothballing or abandoning such a facility should not have negative impact for nation's future testing needs
- Langley VMS is also not strategically important from a longer-term view
 - It is being replaced by the Langley CMF and could be considered for elimination once CMF becomes fully operational

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In summary, the nation needs many of NASA's simulators, but two are not strategically important.

The Ames FFC is really a laboratory rather than a significant, strategically important national test capability. It should be left to survive on its own. If potential users do not materialize, mothballing or abandoning such a facility should not have negative effects on the nation's future testing needs.

From a longer-term perspective, the Langley VMS is also not strategically important. It is being replaced by the new Langley CMF and could be considered for elimination once the Langley CMF becomes fully operational.

The Remaining Research Simulators Show Strong National Needs with Some Redundancy

- **Ames VMS is strategically important to NASA research and is mission critical to the DoD**
- **Ames CVSRF and Langley CMF fill a needed flexible hexapod research capability niche**
 - **Emphasis is on reconfigurable capabilities given workforce and source codes**
- **Langley DMS is unique mothballed facility primarily used by DoD to simulate air-to-air combat in a classified environment**
- **Redundancy between Ames CVSRF and Langley CMF**
 - **Might be a future consolidation opportunity if utilizations are consistently low**
 - **No clear underutilizations at this time**
 - **Workforce differences complicate consolidation**
- **Consolidation simulation capabilities at a single center might be a future, long-range consideration for NASA management**
 - **Does the SCAP management structure consider these kinds of long-range strategic issues?**

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If the Ames FFC and Langley VMS are excluded, the nation needs all the remaining simulators, although some redundancy exists. NASA programs with ARMD have identified testing needs in these facilities, and ESMD has identified these facilities for its long-term strategic needs.

The Ames VMS has been identified as mission-critical by the DoD in the DTRMC study.

The Ames CVSRF and Langley CMF fill a needed flexible hexapod research capability niche. Although industry has many hexapods, the combination of NASA researchers' corporate memory, access to the manufacturers' hexapod control software code, and ability to reconfigure simulator cockpits and displays makes NASA's hexapod capabilities unique.

The Langley DMS is a unique mothballed facility used primarily by the DoD to simulate air-to-air combat in a classified environment on multiple platforms.

There is some redundancy between the Ames CVSRF and the Langley CMF. However, the differences in research staff capabilities at the two centers will introduce challenges if consolidation were to be warranted.

Despite the consolidation challenge between the CVSRF and CMF, long-range consolidation of NASA's simulation capabilities into a single research center (i.e., Ames or Langley) might be a good strategic consideration for NASA management in the decades ahead. This might be accomplished through attrition and new investments rather than through elimination of current capabilities. For example, when new investments are considered (especially for new facilities), the location of those capabilities at a designated, primary NASA simulation center

would allow NASA to evolve to a state in which its simulation capabilities are centralized. This would reduce redundancies and facilitate the use and development of NASA's simulation staff. It is unclear whether the current SCAP management structure considers these kinds of long-range strategic possibilities. (SCAP is the agency-level asset program chartered to identify, prioritize, and manage a select suite of NASA key capabilities that are deemed to be essential to the future needs of NASA or the nation, including some capabilities that lack an adequate business base over the budget horizon. ATP is considered part of SCAP but reports directly to ARMD.)

Conclusions and Recommendations

Outline

- Summary of key findings
- Background
- Wind tunnels and propulsion test facilities
- Simulators
- **Conclusions and recommendations**
- Appendix A: NASA, DoD, and industry input details
- Appendix B: Simulator descriptions
- Appendix C: Technical discussion of simulation and simulators

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We now turn to the overall conclusions and recommendations.

NASA's Aeronautics Test Facility Capabilities Remain Important for National Strategic Needs

- These capabilities continue to be strategically important to aeronautics research, defense, commercial, and space sectors
- We expect utilization to remain mixed over time, causing management challenges
 - Reflects program development ups and downs
 - Requires long-term strategic perseverance and diligence
 - Causes continued need for some shared financial support (e.g., from ATP)
- 27 of 31 WT/PT and 4 of 6 simulation facilities should be kept and managed strategically
 - One WT/PT facility (Langley LTPT) has dropped from the user community strategic needs
 - One hypersonic facility in the Langley suite should be dropped from the list
 - Two prior WT/PTs are still not strategically important
 - Simulators also need cross-enterprise strategic management
 - Consider mechanisms to avoid mothballing strategically important facilities
- NASA has done a good job to date of already closing WT/PT facilities that were redundant or not needed
 - 13 additional WT/PT facilities had already been closed by NASA since 1990

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Overall, NASA's aeronautics test facility capabilities remain strategically important for serving the national strategic needs of the aeronautics research, defense, commercial, and space communities.

We measured and derived national *strategic* need and importance from an engineering perspective, asking expert engineering designers and test facility users to explain their long-term strategic testing needs as determined by the *types of vehicles the country produces now or may produce in the future* and from the perspective of the practical budgetary constraints they face generally.

We expect facility use to continue to vary from year to year and from facility to facility, causing important management challenges. This reflects the ups and downs of RDT&E programs and the historical reduction in the frequency (but not elimination) of programs across the range of aeronautic vehicles. This variation in use implies that NASA management will need to take a diligent, long-term strategic view to preserving strategically important capabilities. As we recommended in our prior study (Antón et al., 2004a), this will require shared financial support to keep facility prices stable, competitive, and commensurate with individual testing value. NASA should continue to provide this strategic management and shared support (e.g., as it is currently doing through the NASA ATP).

The U.S. needs for WT/PTs have not changed significantly since our prior study. However, the realities of ongoing low utilizations at certain facilities have logically driven some NASA management actions.

WT/PT Facilities

There were 31 NASA WT/PT facilities during our prior study that meet our study criteria, although NASA had already closed an additional 13 other facilities since the early 1990s. Of these 31, twenty-nine facilities were rated as strategically important in our prior study. Twenty-seven remain so, but two should be removed from that list. The two other facilities identified as not strategically important in our prior study remain so.

The formerly weak strategic support from the user community for the Langley Low-Turbulence Pressure Tunnel has declined even further, and there are no current NASA program needs for it. Boeing (the only prior industrial advocate) suggested that NASA invest in new capabilities at an alternative facility, such as the Langley National Transonic Facility, to provide two-dimensional testing capability similar to that offered by the Langley LTPT. Since significant investment is required to keep the LTPT operational, it would make sense to mothball it while investigating options and issues for expanding the NTF to cover these needs.

Also, one hypersonic facility in the Langley hypersonic suite continues to have poor support and should be removed from the list of strategically important facilities. However, it is important to note that the remaining facilities in the Langley suite serve strategically important needs, so the overall suite cannot be closed. Closing one part of this needed suite will not likely save much money.

Within the 27 strategically important facilities, two have not been used recently, driving them to be mothballed. First, the Ames 12-Foot Pressure Wind Tunnel (PWT) has not been used since our prior study. Thus, NASA actions to mothball it make sense. The Ames 12-Foot is still the only high-Reynolds number subsonic facility in the nation, yet users have been using facilities in the United Kingdom and France for technical and availability reasons. This has caused a de facto reliance on foreign facilities for a strategically important U.S. test capability need. Even so, except for Boeing, there have been no strategic agreements with these foreign facilities to ensure security and access. Thus far, there has been no negative effect except for security concerns from testing overseas, but if access were denied in the future, this could lead to additional problems.

Second, the Glenn Hypersonic Test Facility remains strategically important and unique (because of its nonvitrified heating elements), but a lack of use has forced NASA to mothball the facility in an attempt to preserve what capabilities it can.

Simulation Facilities

Our assessment is that four of the six facilities under study should be kept and managed as strategically important. One of the other two is scheduled to be replaced by a new facility that is nearing operational capability, and the other is a small, relatively inexpensive visual flight control laboratory that has no current NASA or FAA needs and very few potential users elsewhere.

NASA's ATP Is Addressing Strategic WT/PT Issues, But More National Progress Is Needed

- **NASA's ATP reflects strategic needs, and its progress appears in agreement with our findings**
 - Identifying and maintaining its minimum set of strategically important facilities
 - Identifying shared financial support to keep its underutilized but essential facilities from entering financial collapse
 - Trying to address the backlog of maintenance, but ATP does not have large resources to address major improvements
- **Lack of federal investments in new, more advanced facilities is forcing the retention of aging and sometimes inferior infrastructure for strategically important capabilities**
- **NASA and the nation need to continued developing an aeronautics test technology vision and plan**
- **National reliance and consolidation remain the next challenges**
 - NASA and the DoD
 - Government and industry

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The goals, objectives, and actions of NASA's ATP reflect the strategic needs discussed earlier, and ATP's progress appears to be in agreement with our findings. These include identifying and maintaining a minimum set of strategically important test capabilities and identifying shared financial support to keep underused but essential facilities from financial collapse.

However, the lack of federal investments in new, more advanced facilities is forcing the retention of aging and sometimes inferior infrastructure for strategically important capabilities. See, for example, the discussion in Antón et al. (2004a) concerning the lack of support for new facilities and the technical comparisons of NASA facilities to other facilities in Antón et al. (2004b).

Still, NASA and the nation need to continue developing a vision for aeronautics test technology and a plan in response to the new national aeronautics policy (National Science and Technology Council, 2006). Also, national reliance and consolidation remain the next challenges, including between NASA and the DoD, as well as between the government and industry.

Future Issues and Questions Remain

- What additional functions should SCAP undertake to resolve management issues with its simulation facilities?
- How can NASA and the DoD best pursue a shared reliance relationship?
 - What really needs to be changed at the policy and functional levels?
 - What issues remain (e.g., access priorities, ease of access)?
 - What management options make sense?
- What kinds of groundwork can be laid now for international reliance and consolidation considerations?
 - Can allied cooperation result in non-competitive infrastructure supporting a competitive development landscape?
- What can NASA and the United States do to maintain national and world leadership in aeronautics and in test technology?
 - Where is technology going, and where has it become obsolete or second-rate?
- What kinds of facilities will NASA need in the future based on new aeronautics pursuits?
 - For example, to test:
 - UAVs and UCAVs
 - Morphing wings
 - Alternative fuel engines
 - New hypersonic vehicle concepts (missiles, reconnaissance airplanes, space access)
 - Closer aircraft spacing in more crowded U.S. air space
 - Use of GPS for flight control

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Further questions and issues remain that were outside the scope of our study.

For example, ATP has made significant progress in addressing the kinds of issues identified in our prior study for WT/PTs. Simulation facilities appear to have similar needs but are not part of ATP. What additional functions should SCAP undertake to resolve these management issues with its simulation facilities?

Also, how can NASA and the DoD best pursue a shared reliance relationship? What really needs to be changed at the policy and functional levels? What issues remain (e.g., access priorities, ease of access)? What management options make sense?

In addition, what kinds of groundwork can be laid now for *international* reliance and consolidation considerations? Can allied cooperation result in noncompetitive infrastructure supporting a competitive development landscape? That is, can we reliably consolidate and jointly share an international test infrastructure in a cooperative reliance model—despite international political or economic differences or tensions—with companies that develop competitive products.

Furthermore, what can NASA and the United States do to maintain national and world leadership in aeronautics and in test technology? For example, where is technology going, and where has it become obsolete or second-rate?

Finally, what kinds of facilities will NASA need in the future based on new aeronautics pursuits, such as morphing wings, alternative fuel engines, new hypersonic vehicle concepts, closer aircraft spacing in more crowded U.S. air space, formation flying, and an expanded use of GPS for flight control? The nation has been fortunate in that its historical and ongoing test

capability investments have resulted in a very flexible infrastructure that continues to serve its testing needs. However, we need to continue asking whether new aeronautics concepts being researched today will require new test capabilities in the future.

NASA, DoD, and Industry Input Details

Outline

- Background
- Wind tunnels and propulsion test facilities
- Simulators
- Conclusions
- **Appendix A: NASA, DoD, and industry input details**
- Appendix B: Simulator descriptions
- Appendix C: Technical discussion of simulation and simulators

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Appendix A provides additional details on the inputs we received about testing needs from NASA, the DoD, and industry for WT/PT and simulators.

Current NASA ARMD and ESMD Programs Identified Testing Needs for These Facilities

			ARMD										ESMD
			Aviation Safety				Airspace		Fundamental Aeronautics				
Sonic Speed	Center	Facility	Aircraft Aging and Durability	IVHM	IRAC	IIFD	ATM: Air-portal	ATM: Air-space	Fixed-Wing Subsonic	Rotary-Wing Subsonic	Super-sonic	Hyper-sonic	
Sub	Ames	12-Foot (M)											
	Ames*	NFAC 80x120											
	Ames*	NFAC 40x80											
	Glenn	Icing WT											
	Glenn	9x15-Foot											
	Langley	14x22-Foot											
	Langley	20-Foot Spin											
	Langley	12-Foot Lab											
	Langley	LTPT											
Tran	Ames	11-Foot											
	Glenn	8x6-Foot Prop											
	Langley	NTF											
	Langley	TDT											
	Langley	16TT (closed)											
Super	Ames	9x7-Foot											
	Glenn	10x10-Foot Prop											
	Langley	4-Foot											

RANDFacilities identified as needed for current program(M) Mothballed by start of current study
* NASA owned; USAF operated

This slide shows the subsonic (Sub), transonic (Tran), and supersonic (Super) facilities at the NASA Ames, Glenn, and Langley research centers for which we could identify NASA needs in the ESMD and ARMD. These needs are for the NASA programs as currently defined and planned. Thus, they do not reflect needs that might arise from NASA as these programs evolve or are restructured over time. Note that this slide lists only facilities for which NASA needs are identified; facilities not listed had no identified need from NASA programs.

Current NASA ARMD and ESMD Programs Identified Testing Needs for These Facilities (Concluded)

			ARMD										ESMD
			Aviation Safety				Airspace		Fundamental Aeronautics				
Sonic Speed/ Propul- sion	Center	Facility	Aircraft Aging and Durability	IVHM	IRAC	IIFD	ATM: Air- portal	ATM: Air- space	Fixed- Wing Subsonic	Rotary- Wing Subsonic	Super- sonic	Hyper- sonic	
Hyper	Langley	20-Inch M6 CF4											
	Langley	20-Inch M6 Air											
	Langley	31-Inch M10 Air											
Hyper-Prop	Ames	Direct-Connect Arc (M)											
	Ames	16-Inch Shock (M)											
	Glenn	HTF (P)											
	Glenn	PSL-4											
	Langley	8-Foot HTT											
	Langley	Arc Heated Scramjet											
	Langley	Combustion Heated Scramjet											
	Langley	Direct-Connect SS Combustion											
	Langley	15-Inch M6 HTT											
	NASA*	HYPULSE											
Prop	Glenn	PSL-3											
	Glenn	ECRL-2B											

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 Facilities identified as needed for current program

(M) Mothballed by start of current study

(P) Mothball preservation started during current study

* NASA owned; GASL operated

This slide shows the hypersonic wind tunnels (Hyper), hypersonic propulsion-integration facilities (Hyper-Prop), and the direct-connect propulsion test facilities (Prop) at the NASA Ames, Glenn, and Langley research centers for which we could identify NASA needs in the ESMD and ARMD. Again, we listed only those facilities for which NASA needs are identified; facilities not listed had no identified need from NASA programs.

Responses from DoD Users in DTRMC Study Identified Critical and Other Needs for WT/PT Capabilities

Speed	Center	Facility	USAF	Navy	Army	MDA	DDR&E
Subsonic	Ames	12-Foot					
	Ames	NFAC 80x120		X	X		
	Ames	NFAC 40x80t		X	X		
	Glenn	Icing WT	X	X	X		
	Langley	14x22-Foot	Research Support after Modifications	Forced Oscillation & Free Flight Testing			
	Langley	20-Foot Spin	X	X			
Transonic	Ames	11-Foot	X	X			
	Glenn	8x6-Foot	Primary AEDC 16T				
	Langley	NTF	X	X			
	Langley	TDT	X	X	X		X
Supersonic	Ames	9x7-Foot	X	X			
	Glenn	10x10-Foot	Primary AEDC 16S	Primary AEDC 16S		Primary AEDC 16S	

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Facilities identified as "critical"

Additional non-critical needs and potential uses

Source: DTRMC study (AT&L, 2007)

The DTRMC study (AT&L, 2007, and associated unpublished data) provided information about which subsonic, transonic, and supersonic WT/PTs the DoD identified as mission-critical and as strategically important. The comments on the facilities identified as strategically important provide the rationale behind the survey responses. For example, the Glenn 10x10-Foot was identified as a useful backup capability, and the AEDC 16-Foot Supersonic WT (16S) is listed as the primary DoD supersonic propulsion WT facility. Note, however, that 16S has been mothballed for years, and significant investment would be required to make it operational. As a result, the Glenn 10x10-Foot, which is currently operational, can be made available for supersonic testing for the DoD. Similarly, the Ames 9x7 supersonic WT is another strategically important, currently operational supersonic capability alternative to the AEDC 16S.

Likewise, the Glenn 8x6-Foot transonic propulsion WT is a useful backup capability for the AEDC 16-Foot Transonic propulsion WT (16T). Also, the Langley 14x22-Foot subsonic WT has some DoD research support (if planned modifications are completed) and is a strategically important facility for forced oscillation and free flight testing.

Responses from DoD Users in DTRMC Study Identified Critical and Other Needs for WT/PT Capabilities (concluded)

Sonic Speed/ Propulsion	Center	Facility	USAF	Navy	Army	MDA	DDR&E
Hypersonic Propulsion Integration	Glenn	HTF	Noted uniqueness; Could TBCC engine development need non-vitiated testing?				
	Glenn	PSL-4	Primary AEDC	Primary AEDC			
	Langley	8-Foot HTT	Backup after AEDC APTU* upgrade	X			
	Langley	Arc-Heated Scramjet	No known alternatives exist				
	Langley	Combustion-Heated Scramjet	No known alternatives exist				
Direct-Connect Propulsion	Glenn	PSL-3	Primary AEDC	Primary AEDC			
		PSL-4	Primary AEDC	Primary AEDC			

 **Facilities identified as "critical"**
Source: DTRMC study (AT&L, 2007)
 **Additional non-critical needs and potential uses**
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*Planned to be upgraded to Mach 8

Of the hypersonic and direct-connect propulsion WT/PTs, only the Langley 8-Foot HTT was deemed mission-critical by the DoD (AT&L, 2007). These needs included those from the USAF, Navy, Army, Missile Defense Agency (MDA), and the Office of the Director, Defense Research and Engineering (DDR&E). The Langley HTT will remain a backup facility after the planned upgrade of the AEDC Aero and Propulsion Test Unit to Mach 8.

A number of other NASA capabilities had noncritical needs and potential uses. The Glenn HTF was recognized as a unique facility (because of its nonvitiated heating core) and potentially useful for testing Turbine-Based Combined Cycle (TBCC) engines. The Langley Arc-Heated Scramjet and the Langley Combustion-Heated Scramjet capabilities were deemed strategically important because no known alternatives exist. The Glenn PSL facilities (PSL-3 and PSL-4) are useful (but not DoD-critical) backup facilities for the AEDC.

NASA ESMD Constellation Identified Possible Simulator Needs			
	Crew Exploration Vehicle (CEV)	Lunar Lander	Mission Ops
Ames Vertical Motion Simulator (VMS)	• Motion cues to assess manual control capability (possibly mid-FY08 to FY10) • Other facility options may be available	• Possible use for DDT&E and crew training	• Possible CEV crew training (out years) • Possible use for LSAM lunar descent and ascent training • Do not know yet about use for CEV pilot training
Ames Crew-Vehicle Systems Research Facility (CVSRF)		• Possible use for mission simulation and crew training	
Ames Future Flight Central (FFC)			
Langley Cockpit Motion Facility (CMF)	• Test and design user interfaces such as RHC, abort engage, and cursor-control devices during vibration and g-loads • Breakout forces, operating forces, and usability assessment • Short duration (2-3 weeks) in mid-2008 • Other facility options may be available	• Possible use for DDT&E and crew training	
Langley Visual Motion Simulator (VMS)	• Possible use with, or in place of, the Langley CMF to meet the same objectives shown in the CMF • Other facility options may be available	• Possible use with or in place of the Langley CMF	
Langley Differential Maneuvering Simulator (DMS)		• Possible use for DDT&E and crew training if space-related simulation capability is added	
RAND			

This slide lists the possible needs from ESMD's Constellation program for the simulators we examined. Constellation is NASA's program to build the Crew Exploration Vehicle (CEV), launchers, and landing spacecraft for its effort to return astronauts to the moon. These are long-term strategic needs and should not be construed as definite. ESMD has no projected simulator needs beyond these in the Constellation program.

Of all these simulation capabilities, only the Ames FFC had no possible testing needs within ESMD.

Note that, as CEV program requirements mature, its testing needs and facility requirements will be assessed to provide the most cost-effective approach. Also, the inputs received from the Lunar Lander program were an early forecast; firm requirements were not yet defined. Finally, the Crew Launch Vehicle (CLV) program did not identify needs at this point.

Simulator Descriptions

Outline

- **Background**
- **Wind tunnels and propulsion test facilities**
- **Simulators**
- **Conclusions**
- **Appendix A: NASA, DoD, and industry input details**
- **Appendix B: Simulator descriptions**
- **Appendix C: Technical discussion of simulation and simulators**

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Appendix B provides additional detailed descriptions of NASA's simulators.

Ames' Vertical Motion Simulator (VMS) Allows Very-Long Lateral Transversal Movements

- **Unique asset with unrivaled performance**

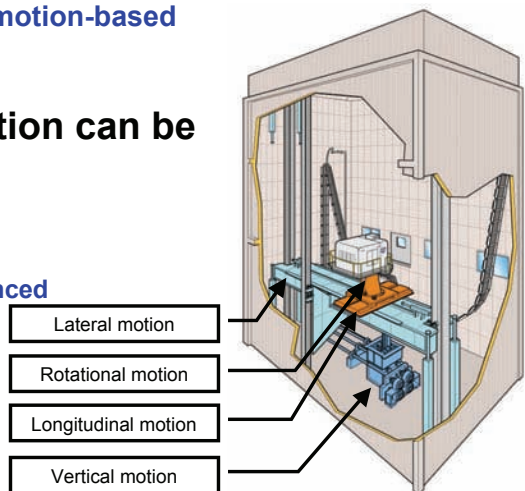
- “The Human Performance Group members also noted that ‘. . .the VMS was far better in its capability to produce realistic motion cues as compared to a typical hexapod motion-based training simulator.’ ”
(Tran and Hernandez, 2004)

- **Lateral and longitudinal motion can be switched if needed**

- **Operational since early 1980s**

- **Construction**

- **70-ton platform; pneumatically balanced**
- **Motor power totaling about 1500hp**



(Source: NASA Ames)

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The NASA Ames VMS is a unique national asset capable of simulating a number of different types of aircraft and spacecraft in a high-fidelity setting. The Ames VMS can have different simulator cabs installed, which can be modified to represent any aircraft or spacecraft so that the operators can physically sit in a realistic cockpit configuration with actual cockpit hardware. Compared to hexapod-type simulators, the Ames VMS has a very large step (i.e., ability to move long distances in a certain direction). The simulator cab attached to the Ames VMS can travel 60 feet vertically and 40 feet horizontally. The large step is key to the high-fidelity simulation and allows the motion to very accurately simulate all phases of flight, even the critical landing and takeoff phases. (See also SimLabs, 2005b.)

Ames Crew-Vehicle Systems Research Facility (CVSRF) Hexapod Installation Is a Flexible Research Facility

- **Ames CVSRF**
 - Two 6-DOF Hexapods
 - Can be linked (e.g., for parallel approach studies)
- **Advanced Concepts Flight Simulator**
 - IOC 1996
 - Reconfigurable flight deck
- **747 Simulator**
 - IOC in 1980s
 - FAA Class-D Certified
 - Flight deck hardware is rarely altered

(see NASA Ames ACFS website; Blake, 1996; and Schroeder, 2007)



CVSRF
ACFS in front, 747 Simulator behind
(Source: NASA Ames, 2005c)

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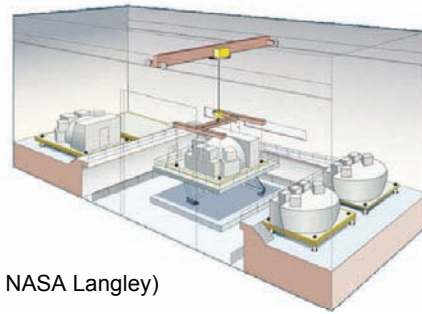
The NASA Ames Research Center currently operates a dual-hexapod simulator facility called the CVSRF. The first hexapod is an FAA-certified Class-D 747 simulator. The flight deck and motion represent a standard Boeing 747-400. This simulator is rarely altered, because doing so would void the FAA Class-D certification and would require that the entire system be recertified for future 747 tests. The 747 simulator had an initial operational capability (IOC) in the 1980s.

The second hexapod is a reconfigurable flight simulator called the Advanced Concepts Flight Simulator. The ACFS was built to represent a generic commercial aircraft flight deck. It had an IOC of 1996.

Both simulators have six degrees of freedom (DOF) and are linked to the Ames Air Traffic Control Laboratory. This laboratory can function as a control facility or as a simple air-traffic generator. (See also Blake, 1996, and SimLabs, 2008.)

Langley Is Developing a New Hexapod Installation: Cockpit Motion Facility (CMF)

- **Currently being tested in preparation for operational certification**
 - Will replace older Langley Visual Motion Simulator (VMS) hexapod
- **6 DOF, 76" leg stroke, 22 k-lbs load**
- **Modular cockpit/visual simulation pods**
 - **Generic Flight Deck:**
generic glass cockpit
 - **Research Flight Deck:**
hybrid B-777/MD-11/A320
 - **Integration Flight Deck:**
modified B-757



(Source: NASA Langley)

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NASA Langley Flight Research Center's CMF, which is scheduled to replace the VMS at Langley, is a hexapod with three interchangeable cabs. These cabs allow simulations both in stationary mode (off the hexapod) and with motion while on the hexapod. The three current simulator cabs are the Generic Flight Deck (GFD), the Research Flight Deck (RFD), and the Integration Flight Deck (IFD). Each flight deck can be modified to represent a number of different aircraft and spacecraft.

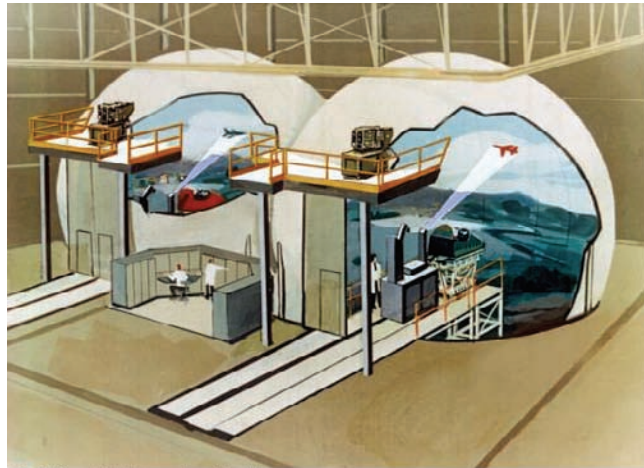
The RFD was the first cab built for the CMF. The RFD represents a state-of-the-art subsonic transport aircraft. It combines the features of many commercial aircraft, including the Boeing 747 and 777, the McDonnell Douglas MD-11, and aircraft from the Airbus A300 series. The RFD is a highly reconfigurable flight deck and has also been used to represent NASA's Transport Systems Research Vehicle—a Boeing 737 used by NASA for flight research.

The IFD was built as a copy of the flight deck of NASA Langley's Boeing 757-200, which was stationed at Langley until recently. The controls and motion are copied from that of the actual B-757. Though the controls are specified for the B-757, the structural components for the IFD are almost identical to those of the RFD.

The GFD is the newest addition to the CMF facility. The GFD can be configured to represent many different aircraft and spacecraft. The cab has nine large flat-panel displays, and it can employ either a center wheel column, center stick, or side sticks for control. The GFD has been used to test conceptual plans for cockpits.

Langley Differential Maneuvering Simulator (DMS) Caters Primarily to DoD Needs

- **Has two 40-foot visual domes to simulate air-to-air combat**
 - **Similar contractor simulators are dedicated to specific platforms**
 - Lockheed Marietta F-22 and the Boeing St. Louis F-15, etc.
- **Research facility:
Reconfigurable to multiple
platforms**
- **Currently mothballed**



(Source: NASA Langley)

RAND

The Langley DMS caters primarily to DoD needs. This facility has two paired 40-foot domes designed for air-to-air combat simulation. The displays are configurable to multiple platforms—a feature not commonly seen within the industry. For example, aircraft manufacturers such as Boeing and Lockheed Martin typically have dedicated facilities for platforms such as the Boeing F-15 and the Lockheed Martin F-22. The DMS domes allow each pilot to have a nearly spherical field of view (FOV). The wide FOV simulates six DOF while maintaining a fixed, nonmotion base for each cockpit. The fixed base simulator also simulates engine and wind sounds, as well as cabin vibrations. (See, for example, Ashworth and Kahlbaum, 1973). The facility is currently mothballed. When tests are conducted, the user funds the effort to get the facility back to operational status and also to return it to mothball status once the tests have been completed.

Ames Future Flight Central (FFC) Simulates a Control-Tower Team and Display Environment

- **360 degree visual display of traffic around and on an airport**
 - **Primarily a room with surrounding displays and supporting processors**
- **Research areas**
 - **Runway incursion**
 - **Air traffic management**
 - **Control tower protocols under different air traffic scenarios in and around an airport**
 - **Human factors research under these conditions**



(Source: NASA Ames)

RAND

The Ames FFC simulates a control-tower environment with a 360-degree visual display of traffic in and around an airport. Typical research areas for this facility include addressing runway incursion, air-traffic management, control-tower protocols under different air-traffic scenarios, and human-factors research under these conditions. Airport managers have shown some interest in this facility. Army researchers at Ames have also shown some interest, suggesting the possibility of using this facility to develop protocols for manned and unmanned systems in a wartime environment such as Iraq. NASA has no program needs for this facility, and the FAA has withdrawn support for it.

The FFC's 360-degree visual displays operate in real time with vehicle simulation controllers on the facility's lower level or with other simulators at Ames. Users of the facility are immersed in the simulation with views all around the simulated position in a way that a single computer screen cannot provide. (See also SimLabs, 2006.)

Technical Discussion of Simulation and Simulators

Outline

- **Background**
- **Wind tunnels and propulsion test facilities**
- **Simulators**
- **Conclusions**
- **Appendix A: NASA, DoD, and industry input details**
- **Appendix B: Simulator descriptions**
- **Appendix C: Technical discussion of simulation and simulators**

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Appendix C provides a technical discussion on simulation design, metrics, and performance.

In Principle, Simulation Involves Deciding Which Real-World Factors Are Relevant to the Question at Hand

- Which must be represented and to what level of fidelity (accuracy and precision)?
- Which are marginal and are nice to have but not critical?
- Which are not important and can be simplified or left out?
- Factors to consider
 - Motion
 - Visual display
 - Realism versus representative, motion, peripheral vision, resolution, etc.
 - Vehicle controls and configuration
 - Realism, positioning, movement
 - Haptic
 - touch, vibration,
 - Sound

RAND

First, it is useful to discuss the benefits of simulations.

From first principles, simulation allows controlled examination of certain aspects of a real-world or theoretical situation. Designing a simulation involves deciding what factors in the real or theoretical world are relevant to the question at hand. Which must be represented and to what level of fidelity (accuracy and precision)? Which are marginal and are nice to have but not critical? Which are not important and can be simplified or left out?

The features of the kinds of aeronautics simulators in this study involve various factors. A key variable is the amount of motion introduced to convey to a test subject a sense of actual motion relative to the simulated movement of the vehicle. Usually, visual displays are provided to convey the sense of motion and to provide feedback on what is happening to the simulated vehicle(s) and the environment. Vehicle configuration and controls are represented, often using actual control devices and other vehicle equipment, to increase realism and to test factors such as control device positioning and its effect on vehicle controllability. Haptic feedback can be added to controls to convey any touch and vibrational sensations that might be felt in real vehicles during certain conditions. Finally, sounds are added to improve the realism and to provide feedback on what is happening in the simulation.

Simulators Are Used for Cost and Safety Reasons to Improve Understanding, Reduce Risks, and Explore New Capabilities

- **Simulators have uses across the range of aeronautics**
 - Research
 - Development
 - Test and evaluation
 - Failure analysis
 - Sustainment
 - Training
- **Provide a controlled environment to reduce risks and explore opportunities and problems**
 - Cost
 - Less expensive than actual flights
 - Danger
 - Push performance and safety envelopes
 - Assessing failure causes
 - Time
 - Rapid exploration of new ideas
- **We must weigh these benefits against the costs of using simulators, especially the most sophisticated ones that provide large motion capabilities**

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Simulators are used for various purposes to understand what happens in real-world situations without having to incur the costs, dangers, or time involved with actual flights. Simulations can be less expensive than performing actual flights and do not expose pilots to the dangers of untested flight conditions. Also, simulators can allow examination of new capabilities and safety envelopes, as well as the root causes of failures in actual flight under a controlled environment. New configurations and concepts can also be examined more rapidly in many cases through simulators.

Of course, simulators come with a cost, and their benefits must be weighed against their cost. Simulators that have greater motion capabilities have higher operational costs than those with smaller or no motion capabilities.

Simulators Play a Strategically Important Role in Vehicle Development and Training

- **Research**
 - Develop flight tasks that simulate real flight scenarios
 - Assess handling qualities with hardware, control system algorithms
 - Assess human-machine interactions/operational protocols
- **New aircraft and spacecraft development**
 - Risk reduction prior to flight testing
 - Existing aircraft and spacecraft
 - Facilitate pilot training
 - Risk reduction

RAND

Simulators play a key role in research and development of new aircraft and spacecraft and pilot training. Research areas include developing flight tasks that simulate real flight scenarios, assessing the handling qualities of hardware, enabling development and refinement of control system algorithms, and examining human-machine interactions and operational protocols. With respect to developing new aircraft or spacecraft, simulators play a strategically important role in risk reduction prior to flight testing. In the case of existing aircraft or spacecraft, simulators facilitate pilot training and thereby reduce risk.

The FAA Has Established Progressively Complex Fixed-Wing Flight Simulator Categories

Number of FAA-registered active simulators (2007):	
0	• Level 1-7 flight training devices (FTD): no motion simulation
0	– Level 1: no requirements
46	– Level 2: correct controls layout, actuation, forces and travel; basic aerodynamic simulation; correct navigation equipment
1	– Level 6: significant sounds, but not all aero and controls effects
	– Level 7: highest requirements (sounds, special aero effects, etc.)
	• Level A-D full-flight simulators (FFS): motion simulation
21	– Level A: 3DOF, control forces and travel, <300 ms lag for motion/visual cues, cues representative of real airplane
20	– Level B: + aero ground effects, reverse thrust, runway rumble
214	– Level C: + 6DOF, wind shear effects, <150 ms lag, 75° FOV
348	– Level D: + more aero effects (icing, Mach), buffeting (gear, flaps)
Total: 650	

(Sources: FAA, 1991, 1992, 2007)

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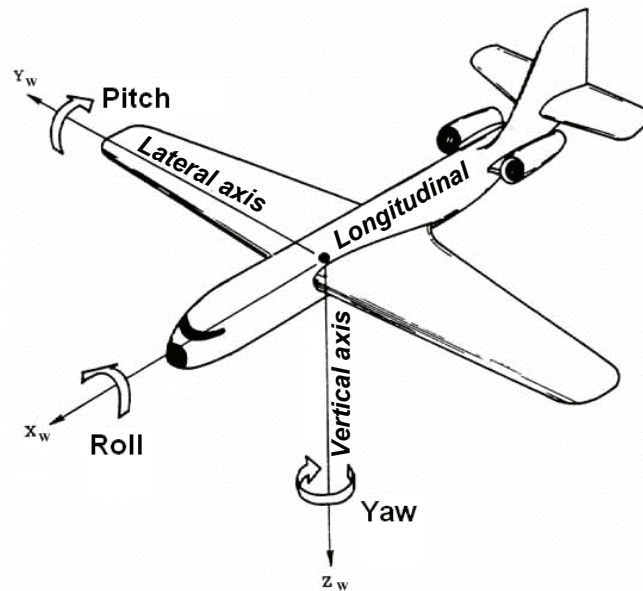
The FAA divides flight simulation devices into two distinct categories. Simulators that do not include motion simulation are classified as Flight Training Devices (FTDs); those with motion simulation are called Full Flight Simulators (FFSs).

FTDs and FFSs are further subdivided according to their level of simulation fidelity. Two FAA circulars, AC-120-40B and AC-120-45A, respectively, define the features that simulators at each level must offer (see FAA, 1991, 1992).

FTDs start at level 1, at which no requirements exist. This level is exemplified by a desktop computer-based flight simulator, such as Microsoft® Flight Simulator X (see, for example, Microsoft, undated) or X-Plane® (see Laminar Research, undated). Successively higher levels of fidelity are achieved by adding a correct mock-up of the cockpit controls and instruments, simulating control actuation forces, and providing a more detailed aerodynamic simulation (level 2), including sounds and detailed aerodynamic effects (levels 6–7).

Full Flight Simulators start at level A, with a three-DOF motion simulation. DOFs selected differ, but, for fixed-wing simulators, they usually include pitch, roll, and vertical acceleration. Motion and visual cues can lag behind the expected “real” behavior up to 300 milliseconds. Level-B fidelity adds simulation of aerodynamic ground effects and runway rumble and enables the pilots to simulate the use of reverse thrust. Level-C and level-D simulators must offer all six DOFs in the motion base. At those levels, lag is limited to a maximum of 150 milliseconds, and the FOV must be significantly larger. Level-D simulators must incorporate the most detailed aerodynamic effects, such as those caused by icing, landing gear and flap deployment, and Mach effects.

Motion Simulators Can Have up to Six Degrees of Freedom



(Adapted from Mahoney, 2004)

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- Lateral
 - Side to Side
- Longitudinal
 - Front to Back
- Vertical (“Heave”)
 - Up and Down
- Pitch
 - Rotational around Lateral axis
- Roll
 - Rotational around Longitudinal axis
- Yaw
 - Rotational around Vertical axis

Motional simulators can have up to the six DOFs illustrated above: lateral, longitudinal, vertical, pitch, roll, and yaw. Six-DOF simulators can move in each of these directions by some amount.

Flight Simulator Performance Metrics

- **The goal of motion in simulators is to reduce risk in actual flight**
- **Handling similarity to real-world vehicle (piloting cues)**
 - **Simulated visual/motion cues must conform to real-world and/or expected behavior of simulated vehicle**
 - Perception of linear and angular acceleration
 - Including magnitude, rate, duration, frequency
 - Synchronization of visual and motion cues
 - **Pilot-in-the-loop stability analyses and human-factors studies require high degree of similarity**
- **Vibrations, noise, and other effects**
 - **Contribute to pilots' sense of immersion**
 - **Can also provide valuable piloting cues**
- **Tactile cueing: simulation of stick/column and pedal characteristics**
- **For research simulators: adaptability to different systems**
 - **UAVs, supersonic/hypersonic vehicles, etc.**

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The quality of motion simulation plays a critical role in the fidelity and, thus, utility of a simulator. Pilots expect a simulator to “handle” like the real-world aircraft it represents. This requires that both visual and motion cues conform to the expected behavior of the vehicle and are synchronized with each other. Although visual simulation, along with the instruments, creates a sensation of position and motion, the motion base must simulate the acceleration cues. Ideally, the magnitude, rate of onset, duration, and other waveform parameters are emulated by the motion base. However, mechanical restrictions almost always necessitate compromise. This issue will be illuminated in subsequent slides.

Similarly, handling plays a particularly important role if the simulator is used to perform pilot-in-the-loop stability analyses and human-factors studies.

Additional effects that a motion base can provide are the higher-frequency vibrations exhibited by an aircraft (e.g., during the takeoff run or during turbulence). These effects contribute mainly to the pilot's sense of immersion into the simulation, but they can also provide valuable piloting clues.

In addition to the motion of the overall cockpit by the motion base, proper simulation of the dynamic characteristics of control inputs such as sticks, control columns, throttles, and pedals has an important effect on the realism of a simulation. To provide this tactile cueing, a simulator needs high-quality control loader systems to replicate control motion characteristics such as resistance, force feedback, overtravel, damping, free-play, and others.

A different performance indicator of a flight simulator is its adaptability to different simulation needs. Although most commercial simulators are used for training and therefore need to

closely replicate existing aircraft, simulators at NASA and the various aircraft manufacturers are often used to simulate notional or experimental aircraft and must therefore support a wide range of cockpit configurations, flight and vehicle dynamics models, and accelerations.

Flight Simulator Motion Issues

- **Motion improves simulation results in cases of dynamic maneuvers and high-workload situations (refueling; edge of stability envelope)**
- **Practically impossible to have 100-percent realistic motion simulation throughout flight envelope**
 - **Always are limits in transversal or motion in a certain direction**
- **Issues with poor motion synchronization**
 - **Flight dynamics versus visual/physical motion feedback can invalidate design test or training results**
 - **Visual versus physical motion can cause motion sickness**
 - **Technology improvements have reduced lag**
 - **1970s: >300 ms lag**
 - **2000s: <100 ms lag**

(Sources: Schroeder, 1999; Gabbai, 2001; Schroeder, not dated)

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As mentioned earlier, mechanical restrictions on the motion bases make it impossible to achieve a 100-percent realistic simulation of motion. Therefore, feasible motion simulation is always degraded in some way.

Such degraded simulation can have deleterious effects on certain simulation tasks, which are therefore better done without motion at all than with degraded motion. Excessive differences in phase, magnitude, and duration between the perceived motion provided by a simulator and the actual motion calculated by the flight dynamics model (and experienced in a real aircraft) can invalidate the desired training effect and can even teach pilots the wrong responses. Additionally, a perceivable divergence between the physical motion cues provided by a simulator's motion base and its visual simulation system can cause motion sickness in pilots.

Motion bases are therefore not considered essential to training activities involving large, slow-moving aircraft such as commercial transports, but they do improve the training outcomes in case of certain highly dynamic and workload-intensive flight profiles such as aerial refueling and flying at the edge of an aircraft's stability envelope.

Technology improvements over the past several decades have significantly improved the synchronization and lag issues caused by slow simulation computers and mechanical controls. Lag times of under 100 milliseconds, which can barely be perceived, are now standard. Even lower times have been achieved by experimental simulators at the expense of overall range of motion (for example, the SIMONA research simulator at the Delft University of Technology; see Delft University of Technology, undated).

However, the restrictions imposed by the displacement limits of motion bases, and the resulting necessary use of high-pass “washout” filters in their controls architecture, impose a phase error that cannot be avoided.

For further discussions, see Schroeder (1999), Gabbai (2001), and Schroeder (not dated).

Simulating Acceleration Is a Key Challenge

- **Simulator needs to compensate for limits of platform travel**
- **Short-term accelerations: acceleration onset cueing**
 - Simulator delivers initial “kick” of acceleration that subsequently fades out
 - Simulator then slowly returns to original position (“washout”) at a lower rate—ideally below the pilot’s sensory threshold
 - Achieved through a high-pass filter
- **Longer-term acceleration: tilt coordination**
 - Uses gravity to create illusion of fore/aft or lateral acceleration
 - Example: the simulator platform, including cockpit and visual assembly, is tilted nose up to simulate take-off run acceleration
 - Requires slow onset to avoid perception of rotation

(Sources: Schroeder, 1999; Gabbai, 2001)

RAND

To understand the restrictions on motion simulation fidelity imposed by the displacement limits of the motion base (whether in the Ames VMS or in a general hexapod style), it is necessary to take a more detailed look at how flight simulators create the impression of dynamic motion (i.e., provide the appropriate acceleration cues to the pilots).

Short-term accelerations—like those caused by changing the attitude angles of the aircraft—are simulated by a technique called acceleration onset cueing. This approach has the simulator motion base deliver an initial “kick” of acceleration that subsequently (within less than one second) fades out, before the motion base is slowly returned to its original “neutral” position. Ideally, the fade-out and return take place below the sensory threshold of the pilots in the simulator, thus providing them with the impression of continued acceleration. However, this *washout* is still felt by most pilots, especially in case of large initial accelerations.

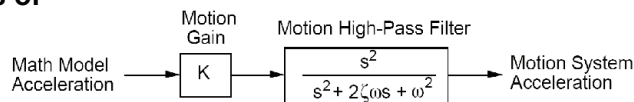
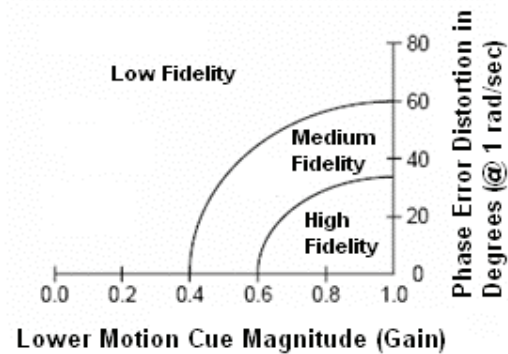
In practice, this washout process is controlled by a high-pass filter in the control chain between the mathematical model and the simulator motion-base hardware. Although most simulators use a second-order filter, first- and third-order filters are used as well. As with all filters, this approach inevitably introduces a phase error.

Longer-term accelerations are generally simulated through *tilt coordination*. This technique tilts the cockpit platform by a small angle, thus using gravity to create the sensation of constant translational acceleration. For example, to create the 30 seconds or so of aft acceleration experienced during an aircraft’s takeoff run, the simulator platform would be tilted nose up, which pushes the pilots “back” into their seats. To avoid the pilots noticing the reduced “down” force resulting from this approach, tilt angles are generally limited to 10 degrees, and the tilt rate must be limited as well.

For further discussions, see Schroeder (1999) and Gabbai (2001).

Flight Simulator Motion Performance

- Gain and phase errors are caused by the high-pass motion filter between math model (“real” values) and simulator motion base
 - Filter is needed to constrain motion to mechanical limits of base
 - Filter blocks steady-state values, but passes transients
- Phase error: “lead” of motion
 - Adjusted by filter parameter ω
- Gain: simulator (output) motion / real (input) motion
 - Adjusted by filter parameter K
 - Also affected by filter parameters ω , ζ
- Trade-off between simulation fidelity and performance/cost limitations of mechanical system



(Sources: Schroeder, 1999; Schroeder, not dated)

RAND

As mentioned before, the use of a filter is necessary to limit the maximum displacement of the motion platform. A high-pass filter, which blocks steady-state values but passes transients, inevitably introduces a phase error. This phase error, defined as the phase shift between the filter's input and output waveforms, causes a “lead” between the simulator's actual motion and the motion commanded by the simulator's ideal flight dynamic model. Although the phase error can be influenced by setting the filter frequency ω , ω also affects another filter effect, the gain, which is defined as the filter's output amplitude divided by its input amplitude. The gain is influenced by the damping ratio ζ and the gain parameter K as well.

Finding the right combination of filter parameter values is therefore a challenging task that depends heavily on the specific type of simulation that is desired. The trade space between gain, phase error, and resulting perceived fidelity of motion is shown in the figure, which plots the characteristic gain and phase error calculated for a steady-state sinusoid input at 1 radian/second. Increasing the range of motion that is supported by the motion base enables higher-fidelity filter settings, but this comes at the price of higher cost and complexity.

Note that, if the filter type and all its parameters are known, its gain and phase shift can be calculated for all input frequencies and waveforms.

For further discussions, see Schroeder (1999, not dated).

State-of-the-Art in Simulator Technology

- **Limiting factors**
 - **Maximum displacement of motion base**
 - Resulting limited duration and magnitude of accelerations
 - **Visual system (resolution, field of view, etc.)**
 - Resulting limitation of visual cues
- **Most widespread motion base: Hexapod**
 - **Creates dependencies among degrees of freedom**
- **Available computing power is sufficient for detailed representation of aerodynamics and other elements**

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In summary, the level of fidelity of current flight simulator technology is largely driven by the limitations imposed by motion bases. Hexapod motion bases, while in widespread use and relatively affordable compared to the Ames VMS design, are subject to additional limitations because of the inevitable linking of DOFs.

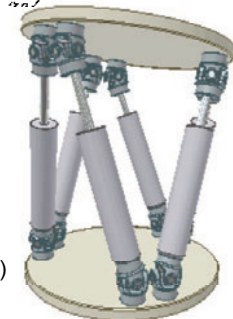
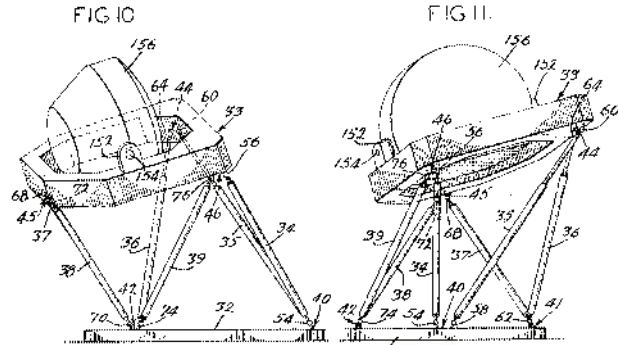
The visual system affects simulation fidelity as well, with such factors as resolution, FOV, and level of detail driving the realism of the visual cues. Current challenges include low-light visualization and image resolution.

Because of advances in computing power, the simulation of detailed aerodynamic effects is no longer an issue, at least for the level of detail demanded for pilot training and handling quality research.

Hexapods Use Six Actuators to Simulate Motion in All Six DOFs

- **Patented in 1967**
 - K. L. Cappel, “Motion Simulator”
- **6 DOFs**
 - DOFs are interdependent
 - Research indicates yaw “axis” can be blocked, which increases available displacement in other axes (Schroeder, 1999, p. 30)
- **Motion filter adapts to cylinder position, causing nonlinear behavior**

(Source: Cappel, 1967)



RAND

(Source: UtzOnBike, 2005)

The hexapod motion-base concept was patented in 1967 by U.S. engineer Klaus L. Cappel. Six linear actuators (hence the name *hexapod*) are combined in such a way as to enable displacement of a horizontal platform in three translational and three rotational axes.

To obtain the desired motion, the output of the simulator's mathematical model, which is given in the traditional six DOFs mentioned earlier, is translated into displacement commands for the six actuators. Since each actuator by itself affects all six DOFs, the DOFs become interdependent. This creates another limitation, but also another possibility for trade-offs: By keeping certain less-important DOFs constant, the range of motion in the remaining DOFs increases, resulting in a higher-fidelity simulation for these axes.

Most modern hexapod motion bases use adaptive filters that reduce their gain when the actuators near their displacement limits. While this enables higher gains near the neutral position, it also introduces nonlinearities that further complicate the optimization of filter parameters.

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