TECHNICAL
REPORT

Wind Tunnel and Propulsion Test Facilities

Supporting Analyses to an Assessment of NASA's Capabilities to Serve National Needs

Philip S. Antón, Dana J. Johnson, Michael Block, Michael Brown, Jeffrey Drezner, James Dryden, Eugene C. Gritton, Tom Hamilton, Thor Hogan, Richard Mesic, Deborah Peetz, Raj Raman, Paul Steinberg, Joe Strong, William Trimble

Prepared for the National Aeronautics and Space Administration and the Office of the Secretary of Defense

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Preface

This technical report provides detailed data, observations, and conclusions from a one-year study (from June 2002 through July 2003) examining the nation's wind tunnel and propulsion testing needs and the continuing ability that National Aeronautic and Space Administration's (NASA's) major wind tunnel (WT) and propulsion test (PT) facilities[1] have in serving those needs, identifying new investments needed and any excess capacities within NASA.

This report should be of interest to those in the research development test and evaluation community in NASA, the Department of Defense, and the aerospace industry seeking detailed insights into national needs for WT/PT facility testing, NASA's facilities, and technical considerations for selected non-NASA facilities important to national needs. The report serves as a companion and supports the following monograph:

Antón, Philip S., Richard Mesic, Eugene C. Gritton, and Paul Steinberg, with Dana J. Johnson, Michael Block, Michael Brown, Jeffrey Drezner, James Dryden, Tom Hamilton, Thor Hogan, Deborah Peetz, Raj Raman, Joe Strong, and William Trimble, *Wind Tunnel and Propulsion Test Facilities: An Assessment of NASA's Capabilities to Meet National Needs,* Santa Monica, Calif.: RAND Corporation, MG-178-NASA/OSD, 2004 (referred throughout this report as Anton et al., 2004[MG]).

The study was funded by NASA and jointly sponsored by NASA and the office of the Director, Defense Research and Engineering (DDR&E). It was conducted within the RAND National Defense Research Institute's (NDRI's) Acquisition and Technology Policy Center. NDRI is a federally funded research and development center sponsored by the Office of the Secretary of Defense, the Joint Staff, the unified commands, and the defense agencies.

[1] Throughout this report, we use the term "WT/PT facilities" to mean wind tunnel facilities and propulsion test facilities, that is, the type of NASA facilities we assessed. Since individual facilities within this designation can be either wind tunnel facilities, propulsion test facilities, or both, "WT/PT facilities" serves as a generic term to encompass them all. That being said, when a specific facility is talked about, for clarity, we refer to it as a proper name and, if necessary, include its function (e.g., Ames 12-Foot Pressure Wind Tunnel). As well, the term "test facilities" and "facilities" can be substituted to mean "WT/PT facilities." Of course, NASA owns and operates other types of test facilities outside of WT/PT facilities, but our conclusions and recommendations do not apply to them.

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Summary

This technical report provides detailed data, observations, and conclusions from a one-year study from June 2002 through July 2003, examining the nation's wind tunnel and propulsion testing needs and the continuing place that the National Aeronautics and Space Administrations (NASA's) major wind tunnel (WT) and propulsion test (PT) facilities[2] have in serving those needs, identifying new investments needed and any excess capacities. The study focused on the needs for large (and thus more expensive to operate) test facilities as well as identified management issues facing NASA WT/PT facilities.

The details in this technical report support the major policy observations, conclusions, and recommendations contained in the companion monograph to the study (Antón et al., 2004[MG]).

Approach

Intensive and extensive interviews were conducted with personnel from NASA headquarters; NASA research centers at Ames (Moffett Field, Calif.), Glenn (Cleveland, Ohio), and Langley (Hampton, Va.), which own and manage NASA's WT/PT facilities; the staff of the Department of Defense's (DoD's) WT/PT facilities at the U.S. Air Force's Arnold Engineering and Development Center (AEDC, at Arnold AFB, Tenn.); selected domestic and foreign test facility owners and operators; U.S. government and service project officers with aeronautic programs; and officials in a number of leading aerospace companies with commercial, military, and space access interests and products.

We employed three semistructured interview protocols to provide advanced notice of the study needs and a level of consistency across the interviews. First, we used an interview protocol for our initial on-site visits and discussions with NASA programs, facility managers, and DoD users. Second, we developed a questionnaire to solicit projected utilization of NASA facilities. Finally, we used detailed supplementary questionnaires to solicit additional insights from aerospace vehicle designers in industry and the DoD. These questionnaires probed their strategic needs in each of the six WT/PT facility categories, to probe their pre-

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ferred facilities and acceptable/possible alternatives, the bases being used for facility selections (technical, business environment, etc.), their needs for new facilities, and their assessments of computational fluid dynamics' (CFD's) role in reducing WT/PT facility requirements.

In addition to the work of the RAND Corporation's resident research staff, the study employed a number of distinguished senior advisers and consultants to help analyze the data received and to augment the information based on their own expertise with various national and international facilities.

In addition, the analysis reviewed and benefited from numerous related studies conducted over the past several years.

Perspectives on the Approach

The analytic method used in the study to define needs does not rely on an explicit national strategy document for aeronautics in general, and for WT/PT facilities in particular, because it does not exist. Lacking such an explicit needs document, we examined what categories of aeronautic vehicles the United States is currently pursuing, plans to pursue, and will likely pursue based on strategic objectives and current vehicles in use.[3]

Also, as *enabling infrastructures*, WT/PT facility operations are not funded directly by specific line items in the NASA budget.[4] The study's determination of WT/PT facility needs and the resulting conclusions and recommendations are therefore not based on the federal budget process as a direct indicator of policy dictates of facility need. We determined WT/PT need by identifying what testing capabilities and facilities are required given current engineering needs, alternative approaches, and engineering cost/benefit trade-offs. This, of course, can lead to a bias in the findings because these assessments may be overly reflective of what the engineering field determines is important rather than what specific program managers are willing to spend on testing as a result of program budget constraints. Thus, when a needed facility is closed because of a lack of funding, there exists a disconnect between current funding and prudent engineering need, indicating that the commercial and federal budget processes may be out of step with the full cost associated with research and design of a particular vehicle class and signifying a lack of addressing long-term costs and benefits.

NASA's Ability to Support National WT/PT Facility Needs

Currently, NASA is mostly capable of providing effective quality support to its WT/PT test facility users within and outside NASA in the near term. Instances in which the agency cannot provide effective quality support lie mostly in specific gaps in their capabilities (which are mostly served by non-NASA facilities), in facility closures that endanger unique or important capabilities, and in management and financial support of strategically important facilities (as discussed below). There are important technical and management issues and potentially

[3] Specific projects and plans were obtained from NASA, Office of Aerospace Technology (2001; 2002); NASA (2001a; 2003); National Aeronautics and Space Act of 1958; DoD (2000; 2002); FAA (2002); NRC (2001); Walker et al. (2002); NASA, Office of the Chief Financial Officer (n.d.); AFOSR (2002); and various DoD and commercial research and production plans.

[4] The *construction* of government WT/PT facilities are, however, very large expenditures requiring explicit congressional funding, and certain facilities, such as the National and Unitary facilities, have associated congressional directives regarding operation and intent.

adverse trends that NASA must begin to address more proactively now to stabilize the current situation and address long-term state-of-the-art testing requirements. If the agency does not act, there is a risk that serious deficiencies may emerge in the nation's aeronautics research and development (R&D) and test and evaluation (T&E) capabilities over the next 10 to 20 years. Proactive approaches to mitigate these potential problems have both management and technical dimensions.

What Management Issues Endanger NASA's Facilities?

Most importantly, NASA should identify shared support to keep its minimum set of facilities from collapsing financially as a result of variable utilization. It is important to note that the \$125–130 million annual operating budgets for all NASA WT/PT facilities under study pale in significance to the national aerospace capabilities that they partially enable, including the federal investments in aerospace R&D of between \$32 billion and \$57 billion annually in the past decade and the military aircraft RDT&E funding alone of \$4.5–7 billion a year in the same period.

Within NASA, the primary facility management problem relates to funding these test facilities operated by three autonomous centers in the face of declining R&D budgets. In the extreme case at Ames, the lack of resident aeronautics research programs combined with the center management's strategic focus toward information technology and away from ground test facilities have left the Ames WT/PT facilities without support beyond user testing fees and thus vulnerable to budgetary shortfalls when utilization falls. Two unique Ames facilities needed in the United States have already been mothballed as a result. The other NASA centers with WT/PT facilities—Glenn and Langley—rely heavily on resident research program taxes to cover low-utilization periods in their major test facilities, but center managers do not yet know whether full-cost recovery policies will nullify these funding sources.

If NASA management is not proactive in quickly providing financial support for such facilities beyond what is likely to be available from full-cost recovery pricing, the facilities will be in danger of financial collapse—some in the very near term. In the near term, this market-driven result may allow NASA to reallocate its resources to meet more pressing near-term needs, but the longer-term implications are less certain. In any event, given (1) the continuing need for the capabilities offered by these facilities for the RDT&E of aeronautic and space vehicles related to the general welfare and security of the United States, (2) the "right sizing" NASA has accomplished to date, (3) the indeterminate costs to decommission or eliminate these facilities, (4) the significant time and money that would be required to develop new replacement WT/PT facilities, and (5) the relatively modest resources required to sustain these facilities, care should be taken to balance near-term benefits against long-term risks. Options for obtaining alternative capabilities in lieu of certain facilities are discussed below, but even if these options are exercised, many facilities will remain unique and critical to meeting national needs.

The management solutions—once the problems and NASA's responsibilities for addressing them are well understood—hinge in most part on the dedication of financial resources to preserve important facilities through multiyear periods of low utilization. Management options in terms of who owns and who operates the facilities (e.g., government or private; NASA, DoD, or confederation; NASA-center-centric or centralized) will have various pros and cons, but all will require a mechanism to stabilize and preserve capabilities needed in the long term through lean times. Key to subsequent analysis of these options is the collection and availability of the full costs of operating these facilities as well as the full costs associated with relying on alternative facilities. This report will help provide the motivation to address these policy, management, and cultural problems, ensuring the continued health of the nation's civil, military, and commercial aeronautics enterprises.

The study also identified a few second-order management issues and concepts that warrant mentioning for further analysis consideration: the importance of the test facility workforce, cross-training of facility crews, workforce outsourcing, and possible privatization options.

What Are the Nation's WT/PT Facility Needs?

The United States continues to need WT/PT facilities across all categories of need (strategic, research and development, and production), for all speed regimes and for specialty tests to advance aerospace research and to reduce the risk in developing aerospace vehicles. Utilization is not the overriding metric for determining the need for a particular type of facility. Despite declines in aerospace research and aerospace vehicle production rates in certain areas, the nation continues to pursue performance improvements in past aerospace vehicles types while exploring new vehicles and concepts, resulting in demands for empirical test simulation capabilities met by WT/PT facilities. CFD has made inroads in reducing *some* empirical test simulation capabilities, but CFD will not replace the need for test facilities for the foreseeable future. Flight testing complements but does not replace facility testing because of its high costs and instrumentation limitations.

How Well Do Existing NASA WT/PT Facilities Meet U.S. Needs?

NASA has 31 existing WT/PT facilities grouped by the six facility categories under study. Combining the agency's WT/PT facilities with the engineering design assessments for the vehicles the United States is pursuing now and in the future, *nearly all existing NASA facilities align with one or more need categories important to the country's ability to pursue aeronautic vehicles across NASA's roles of R&D, T&E, and strategic national interests.*

Most (26 of 31, or 84 percent) of NASA's facilities are technically competitive and effective with state-of-the-art requirements. However, there is room for improvement, especially in the high–Reynolds number subsonic category and in reducing the backlog of maintenance and repair (BMAR) across NASA's portfolio. There also has been discussion in the testing community for both large and small investments to improve NASA's test infrastructure, but it was difficult for our expert consultants and the user community to seriously consider large investment candidates given declining budgets, facility closures, and the failure of past efforts to obtain funding for facilities with improved capabilities. Selected challenges, though, such as hypersonics testing, will require additional research to develop viable facility concepts for future investment consideration.

What Are NASA'S Primary Facilities for Serving the Nation's Needs?

Twenty-nine of 31 NASA facilities play a primary role in serving one or more need categories important to the country's ability to pursue aeronautic vehicles across the agency's roles of R&D, T&E, and strategic national interests. Given recent facility closures (about one-third in the past two decades), NASA's set of test facilities (with two exceptions) is now nearly free of redundancy in type and capability *within* NASA.

The two existing backup NASA facilities are the Langley 12-Foot Subsonic Laboratory (a weakly competitive backup facility whose needs could be met by the Langley 14×22-Foot Atmospheric Subsonic Wind Tunnel) and the Langley 16-Foot Transonic Tunnel (a high-use, weakly competitive facility whose needs could be met by using air in the Langley National Transonic Facility or the Ames 11-Foot).

It should be noted that NASA is not the only source of WT/PT facilities serving national needs. The DoD, industry, and foreign facilities are being used and provide competing and sometimes unique capabilities. The technical capabilities of the primary non-NASA facilities that serve national needs are discussed in this report.

Acknowledgments

We are very grateful for the strong support provided by the project sponsors: Dr. Jeremiah Creedon (NASA Associate Administrator for Aerospace Technology during the study), Dr. J. Victor Lebacqz (NASA Deputy Associate Administrator for Aerospace Technology during the study), Blair Gloss (NASA Headquarters), Jean Bianco (NASA Headquarters), Paul Piscopo (OSD/DDR&E), and Ted Fecke (OSD/DDR&E).

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Our team of senior advisers—H. Lee Beach, Jr., Eugene Covert, Philip Coyle, Frank Fernandez, Roy V. Harris, Jr., and Frank Lynch—provided very useful insights and guidance. Frank Lynch contributed many additional technical assessments on testing needs and facility capabilities. Gary Chapman (UC Berkeley) provided insights on computational fluid dynamics. Claire Antón offered insights into vehicle testing needs and NASA capabilities.

At RAND, Jerry Sollinger provided valuable structural insights into our charts and figures during the course of the study. Theresa DiMaggio, Maria Martin, Karin Suede, and Leslie Thornton gave their administrative support throughout the project. Phillip Wirtz edited the manuscript. Last but not least, we acknowledge the very valuable suggestions, questions, and observations from our reviewers, Frank Camm and Jean Gebman.

Abbreviations

16S	AEDC 16-Foot Supersonic Wind Tunnel
16TT	16-Foot Transonic Tunnel
ASC	Air Force Systems Command
AEDC	Arnold Engineering and Development Center
AFB	Air Force Base
AFRL	Air Force Research Laboratory
AFSOR	Air Force Office of Scientific Research
AIAA	American Institute of Aeronautics and Astronautics
APTU	Aero and Propulsion Test Unit
ASE	Aero Systems Engineering
ASTF	Aeropropulsion Systems Test Facility
ATD	advanced technology demonstration
ATT	Advanced Theater Transport
BMAR	backlog of maintenance and repair
BVWT	Boeing V/STOL Wind Tunnel
CFD	computational fluid dynamics
CoF	construction of facilities
CRV	current replacement value
CUBRC	Calspan-University of Buffalo Research Center
DCSCTF	Direct-Connect Supersonic Combustion Test Facility [Langley]
DDR&E	Director, Defense Research and Engineering
DES	detached-eddy simulation
DNS	direct numerical simulation
DoD	Department of Defense
EOH	engine-on hours
ETW	European Transonic Windtunnel
FAA	Federal Aviation Administration
HSCT	High-Speed Civil Transport
HYPULSE	Hypersonic Pulse Facility

JPL	Jet Propulsion Laboratory
JSF	Joint Strike Fighter
LES	large-eddy simulation
LFC	laminar flow control
LTPT	Low-Turbulence Pressure Tunnel
M	meter
MDA	Missile Defense Agency
MRTFB	major range and test facilities base
MOD	[United Kingdom] Ministry of Defence
NASA	National Aeronautics and Space Administration
NASP	National Aerospace Plane
NATA	National Aeronautic Test Alliance
NAVAIR	Naval Air Systems Command
NFAC	National Full-Scale Aerodynamics Complex
NTF	National Transonic Facility
ONERA	Office National d'Etudes et de Recherches Aerospatiales (French Aeronautics and Space Research Center)
OSD	Office of the Secretary of Defense
PAI	propulsion-airframe integration
PDT	Propulsion Development Test
PT	propulsion test
R&D	research and development
RANS	Reynolds Averaged Navier Stokes
RDT&E	research, development, test, and evaluation
RLV	reusable launch vehicle
Rn	Reynolds number
S&C	stability and control
SLI	Space Launch Initiative
SSTOL	super-short takeoff and landing
STVOL	short takeoff and vertical landing
T&E	test and evaluation
TBD	to be determined
TDT	Transonic Dynamics Tunnel
TsAGI	Central Aerohydrodynamic Institute
UAV	unmanned aerial vehicle
UCAV	unmanned combat aerial vehicle
UOH	user occupancy hours
UPWT	Unitary Plan Wind Tunnel

T&E	test and evaluation
WT	wind tunnel
VKF	von Karman Gas Dynamics Facility
VTOL	vertical takeoff and landing

CHAPTER ONE

Introduction

This technical report provides detailed data, observations, and conclusions from a one-year study examining the nation's wind tunnel and propulsion testing needs and the continuing place that NASA's major wind tunnel (WT) and propulsion test (PT) facilities[1] have in serving those needs, identifying new investments needed and any excess capacities. The study focused on the needs for large (and thus more expensive to operate) test facilities and identified management issues facing NASA's WT/PT facilities.

The details in this report support the major policy observations, conclusions, and recommendations contained in the companion monograph of the study (Antón et al., 2004[MG]).

Approach

Intensive and extensive interviews were conducted with personnel from NASA headquarters; NASA research centers at Ames (Moffett Field, Calif.), Glenn (Cleveland, Ohio), and Langley (Hampton, Va.), which own and manage NASA's WT/PT facilities; the staff of the Department of Defense's (DoD's) WT/PT facilities at the U.S. Air Force's Arnold Engineering and Development Center (AEDC, at Arnold AFB, Tenn.); selected domestic and foreign test facility owners and operators; U.S. government and service project officers with aeronautic programs; and officials in a number of leading aerospace companies with commercial, military, and space access interests and products.

We employed three semistructured interview protocols to provide advanced notice of the study needs and a level of consistency across the interviews. First, we used an interview protocol for our initial on-site visits and discussions with NASA programs, facility managers, and DoD users. Second, we developed a questionnaire to solicit projected utilization of NASA facilities. Finally, we used detailed supplementary questionnaires to solicit additional insights from aerospace vehicle designers in industry and the DoD their strategic needs in each of the six WT/PT facility categories, to probe their preferred facilities and acceptable or possible alternatives, the bases being used for facility selections (technical, business environ-

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In addition to the work of the RAND Corporation's resident research staff, the study employed a number of distinguished senior advisers and consultants to help analyze the data received and to augment the information based on their own expertise with various national and international facilities.

In addition, the analysis reviewed and benefited from numerous related studies conducted over the past several years.

Perspectives on the Approach

The analytic method used in the study to define needs does not rely on an explicit national strategy document for aeronautics in general and for WT/PT facilities in particular because it does not exist. Lacking such an explicit needs document, we examined what categories of aeronautic vehicles the United States is currently pursuing, plans to pursue, and will likely pursue based on strategic objectives and current vehicles in use.[2] In some cases, no explicit vehicle planning exists, but the study assessed current uses and determined that future vehicles will need to be produced. For example, we assumed that the country will continue to need commercial and military rotorcraft and military bomber vehicles despite the lack of a strategic document on committing the resources of the country to their research, development, test, and evaluation (RDT&E).

Despite the existence of planning documents that discuss future vehicles, none of them explicitly talk about WT/PT facilities. Thus, this study used the vehicle categories as the basis for an examination of test facility capabilities needed for RDT&E of those vehicles. This analysis examined engineering design principles as evidenced by expert analysis, advocacy, and survey responses from the research and design communities. Thus, national needs for WT/PT facilities are traced back to the vehicles that they enable. If strategic decisions are made in the future that result in these vehicles being no longer needed, then the results of this study can be used to understand which facilities are not needed. For example, if the DoD and commercial sectors decide that rotorcraft are no longer important, then the WT/PT facility needs that support rotorcraft RDT&E can be eliminated. However, lacking an explicit strategic policy decision that says the country will no longer pursue rotorcraft, this study included these needs in the analysis and conclusions. This study does not dictate what vehicles the country should produce; it merely maps what WT/PT facilities the country needs based on the vehicles in evidence that the country is pursuing and apparently will still need based on a review of existing planning documents and strategic positions.

Note also that as *enabling infrastructures*, WT/PT facility operations are not funded by specific line items in the NASA budget,[3] requiring explicit congressional policy directives regarding facility needs. The study's determination of WT/PT facility needs and the resulting conclusions and recommendations are therefore not based on the federal budget

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[2] Specific projects and plans were obtained from NASA, Office of Aerospace Technology (2001; 2002); NASA (2001a; 2003); National Aeronautics and Space Act of 1958; DoD (2000; 2002); FAA (2002); NRC (2001); Walker et al. (2002); NASA, Office of the Chief Financial Officer (n.d.); AFOSR (2002); and various DoD and commercial research and production plans.

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process as a direct indicator of policy dictates of facility need. Because WT/PT facilities are enabling infrastructure for vehicle categories that enter such policy debates, the study focused on those vehicle categories and the pursuits of such vehicles as the bases of engineering analysis. Policies will dictate specific vehicle productions over time in the future; this study addresses which test facility capabilities will enable the United States to produce such vehicles when such policies arise.

Moreover, the study viewed NASA and Congress's request for an assessment of WT/PT facility needs as an opportunity to inform budget decisions rather than as a dictate to explain facility needs as evidenced by current policy budgetary decisions.

The analytic method used in this study defines the specific test facility needs identified in the areas of national security, research, development, production, and sustainment as those required to enable the prudent research, design, and testing of vehicles classes of interest to the United States. WT/PT facility needs were determined by engineering principles to research new aeronautic concepts, explore and select new designs, and validate performance. In the approach, the aeronautic experts who were consulted applied their best judgment on what testing capabilities and facilities are required given current engineering needs, alternative approaches, and engineering cost/benefit trade-offs. These descriptions of needs reflected current and anticipated approximations that are being explored and used to keep WT/PT facility testing to a minimum, but they do not necessarily reflect short-term budgetary pressures within programs. They are the best judgments of the engineering community as to what is needed strategically to produce the next generation of aerospace vehicles in all classes.

This method, of course, can lead to a bias in the findings because the assessments may be overly reflective of what the engineering field determines is important rather than what specific program managers are willing to spend on testing as a result of program budget constraints. For example, the study findings point to a disconnect between current funding and prudent engineering need. Future utilization levels may not reflect the engineering assessments if future disconnects remain. Also, the study found that, in certain places, underfunding of programs has driven those programs to use facilities that are not appropriate to meet their needs but are shortfalls or insufficient compromises rather than prudent capability choices in a market.

The disconnect may also indicate that the commercial and federal budget processes are out of step with the full cost associated with the research and design stages of a particular vehicle class. If, in the extreme case, this process reaches the point in which the federal government decides it can no longer afford to pursue entire vehicle classes both now and in the long term, the results of this study can be used to indicate which WT/PT facilities are therefore no longer needed.

Scope of the Study

While the study focus was on national needs and NASA's WT/PT facility infrastructure, national needs are not dictated or met solely by the agency's test infrastructure; DoD, U.S. industry, and foreign facilities also serve many national needs. Therefore, the study analyzed potential consolidation opportunities *within* NASA's test facility infrastructure and technical considerations for key non-NASA facilities that might alternatively serve national needs. RAND collected data on and analyzed selected DoD and foreign WT/PT facilities to understand the breadth, depth, and quality of these facilities that are similar to NASA's and to develop a base of knowledge for addressing the competitive need for revitalizing existing NASA facilities. However, the study was *not* chartered or resourced to examine the sets of data for these alternative facilities to fully understand consolidation opportunities *between* NASA and non-NASA WT/PT facility infrastructures. Such a broader study, however, is important and warranted based on our findings.

WT/PT Facility Management Issues

This rest of this chapter provides supporting details on management issues in the study discussed in the monograph:

- the effects of NASA's center-centric organization of WT/PT facility support
- the effects of low utilization on facility financial status
- the financing of facility operations
- the need for periodic reviews of facility health
- additional cost/benefit perspectives.

The Effects of NASA's Center-Centric Organization on WT/PT Facility Support

NASA WT/PT facilities have historically been viewed as research and development (R&D) tools in support of research programs in the local NASA research center as well as national resources for RDT&E for users outside the local community. Management of those facilities has been center-centric, with support coming from the center and primarily managed with the center's needs in mind. Support from the center director and research program relationships have therefore been critical to the health and success of local test facilities. It is useful to briefly review how the three primary NASA centers with WT/PT facilities are structured and what that organization has meant for these facilities.

In recent years, Ames's mission has emphasized information technology as the centerpiece of its implementation strategy while retaining aerodynamics as one of its goals in that strategy. Thus, the test facilities at Ames are not in line with the center's primary emphasis. While aeronautics remains in Ames's vision and mission statements, the center management plans to eliminate center funding support for WT/PT facilities.[4] As a result (and with the near elimination of local research programs at Ames), the WT/PT complex at Ames has had to focus on external test and evaluation (T&E) customers to augment its dwindling internal program customer base (see more detailed utilization data in Chapters Three through Eight).

In contrast, Langley and Glenn remain dominated by their centers' missions of aerodynamics and propulsion, respectively.[5] Langley and Glenn have continued to staff and operate their test facilities primarily in support of aeronautics R&D. This is not a trivial difference. R&D facilities focus on flexible access, allowing more time on point to collect and

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[4] Personal communications, 2002.

[5] See www.larc.nasa.gov/about_us/inside_pages/mission.htm (accessed June 2004); "Exploring NASA's Roots: The History of Langley Research Center," NASA Facts #167, April 1992, http://oea.larc.nasa.gov/PAIS/LaRC_History.html (accessed July 2004); NASA Glenn Research Center Strategic Implementation Plan (Fiscal Year 2003); and www.grc.nasa.gov/WWW/PAO/html/history.htm (accessed June 2004).

observe data and providing knowledgeable research staff in support of testers. T&E facilities focus on quality and productivity, working to get customers in and out quickly while running through and processing their large sets of preplanned data points (called "polars") as efficiently as possible. Often, T&E facilities do not have large research or support staff on hand, since users bring their own team and mostly need the facility operated for them. While this may be an oversimplification of the differences, it does highlight the general differences between how facilities are managed and the general user community they serve. In contrast, some R&D facilities can often be operated or reconfigured to satisfy T&E requirements, and vice versa. The facilities do not know the difference. Equipment upgrades (e.g., in data processing or model control) can change the tenor of a facility's capabilities and the uses for which it is most appropriate.

The Effects of Current Low Utilization on Facility Financial Status

Table 1.1 outlines the fundamental implications of current usage and competitiveness on NASA's facilities. Generally, low utilization results in a low-income stream and thus the need to identify shared financial support for the facility. Weakly competitive facilities are generally candidates for upgrade or consolidation.

Despite their importance, many of NASA's important facilities are unhealthy[6] and require the immediate attention of the agency's leadership. Notwithstanding some technical

Table 1.1
Implications of Technical Competitiveness and Current Usage of NASA WT/PT Facilities

Current Usage	Weak	Strong
Good	**1 out of 31 Facilities** **Upgrade or consolidate** • Candidate for upgrade or possible closure • Beware of losing user base during upgrades	**20 out of 31 Facilities** **In good condition** • May need some shared support • Ensure that full-cost recovery does not endanger taxing mechanisms for shared support at Glenn and Langley
Poor	**4 out of 31 Facilities** **Primary** • Collaborate or upgrade • Workforce skills may be deteriorating **Backup** • Candidates for closure or survival on their own • Workforce skills may be deteriorating	**6 out of 31 Facilities** **Candidates for significant shared support** • Workforce skills may be deteriorating

Technically Competitive with State-of-the-Art Needs

[6] The *health* of a particular test facility reflects its viability across a number of dimensions, including strategic importance, technical capabilities, utilization, user advocacy, uniqueness, strength and availability of alternative facilities, and financial situation.

competitive issues discussed earlier, the most pressing health concern facing NASA facilities is the unreliable and dwindling funding stream to keep these facilities open and well maintained, especially in periods of low utilization.

Periodic Reviews of Facility Health

In addition to periodically evaluating national strategic needs, NASA should consider institutionalizing a periodic review of facility health to ensure that it ties upgrades and maintenance to those strategic needs. As we have noted, the process is undeniably fraught with uncertainty and unpredictability, but the pulses across the user community should be taken at regular intervals and compared with one another and with the agency's own detailed technical R&D road maps. These road maps should outline specific testing challenges not only for R&D but for conducting research to address problems that must be resolved in order to produce a vehicle using the concepts.

Additional Cost/Benefit Perspectives

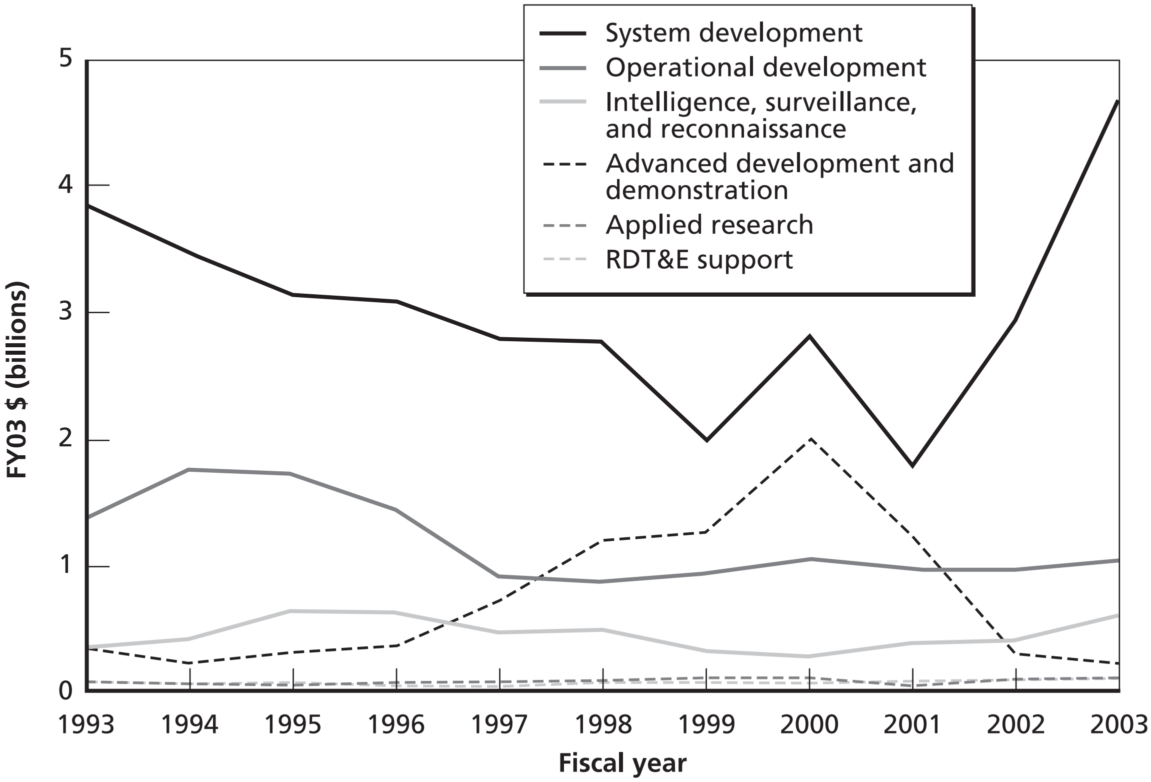
NASA WT/PT facility operating budgets are still a small but more significant part of the amounts paid for systems development. For example, for military fixed-wing aircraft in the past decade, total investments in systems development budgets have run about \$2–4 billion a year, and advanced development and demonstration budgets from \$0.2 to \$2.0 billion a year (see Figure 1.1).

For individual vehicle programs, WT/PT facility costs are also relatively small. To give some perspective from publicly funded programs, the test facility program for representative multiengine military fighters averaged \$37.8 million—only 14 percent of the ground testing costs of \$267 million, or 5 percent of the total system test and evaluation costs of \$796 million. WT/PT facility costs are also low when compared with the \$368 million per year spent on flight testing (Fox et al., 2004).

Enabled Aeronautic Gains. The relative benefits from the facility operating costs may be deceptive, because how these dollars are used can have the long-term benefit of enabling aeronautic RDT&E. These funds provide for the operation of tools vital for aeronautics research and system development. They leverage the scientific and engineering knowledge that underpins aeronautic RDT&E and their effective management will improve long-term outcomes in this field.

NASA test facility operating budgets are relatively small compared with their value in enabling U.S. aeronautics development and reductions in the risks of finding failures in later stages of development (e.g., during flight testing) or not achieving performance targets. Failures can cost a development program months or years and significant redesign and redevelopment costs in the hundreds of millions of dollars and can endanger the development program or even the entire development company. This endangerment is even more critical today, since military aircraft RD&TE funding is increasingly concentrated in a few very large programs; commercial developments are no different. Boeing, for example, "bets the company" on the success or failure of new aircraft development because of the huge amounts of money (billions) invested in RDT&E.

Figure 1.1
Science and Technology Budgets for Military Fixed-Wing Aircraft (FY1993–FY2003)



SOURCE: Birkler et al. (2003).
RAND *TR134-1.1*

At a 2002 NASA workshop on aerodynamic flight predictions, the recent F/A-18E/F wing drop resolution process was reported to have taken an estimated one-and-a-half years and involve more than 100 configurations trials, more than 500 test flights (which can cost as much as $80,000 per test flight), and more than 9,000 windup turns.[7] These added years, trials, and flight tests could have been avoided had more comprehensive facility testing been performed to look for such problems earlier in the program development. In contrast, the successful use of WT/PT facilities and flight predictions of environmental heating characteristics encountered by the tail structure of the Predator during the launch of wing-mounted Hellfire missiles was reported to have saved an estimated 225 days, 65 flight test hours, and $1.4 million.[8]

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[7] A "windup turn" is a flight test maneuver used to establish the longitudinal stability of an airplane, i.e., its tendency to return to its original trimmed flight condition after being disturbed from an initial stable condition (see Hoey, 1997).

[8] Unpublished discussions, NASA/DoD Workshop on Aerodynamic Flight Predictions, 2002.

Organizational Structure of This Technical Report

Each of the following chapters addresses a major topic of the study and the results of our analyses. Note that each chapter ends in a summary that can be skipped to if the reader is not interested in the deeper details of the chapter.

Chapter Two provides details on the national needs for WT/PT facilities.

Chapters Three through Eight provide in-depth analyses of how well NASA's WT/PT facilities serve national needs in each of the six general facility categories under study (see Table 1.2), respectively. We discuss the general approach taken to summarize the study findings in Chapter Three.

Appendix A contains a glossary of some key terms used in this report, including a description of the major WT components. Appendixes B and C provide additional details and Web page references to U.S. and foreign test facilities. Appendix D provides the questionnaires and spreadsheets sent to users and programs to solicit their quantitative and qualitative views and needs for the test facilities under study. Appendix E presents DoD data on construction times for major WT/PT facilities.

Table 1.2
Test Facility Categories for the RAND Study

Test Facility Category	Mach Number Range[a]	Minimum Test Section Size[b]
Subsonic WT	0–0.6	6 feet
Transonic WT	0.6–1.5	4 feet
Supersonic WT	1.5–5.0	2 feet
Hypersonic WT	>5.0	1 foot
Hypersonic propulsion integration	>5.0	1 foot
Direct-connect propulsion	N/A	N/A

[a]Mach number is the ratio between the test speed and the speed of sound at the test conditions. Thus, a Mach number of 2.0 is twice the speed of sound, while a Mach number of 0.5 is half the speed of sound at test conditions.
[b]Nominally, test section size is the diameter of the test section perpendicular to the airflow direction. In wind tunnels where the vertical and horizontal dimensions are of similar magnitude yet differ (e.g., 9 feet high and 15 feet wide), we considered the largest dimension against this criterion.

CHAPTER TWO

National Wind Tunnel and Propulsion Test Facility Needs and NASA's Primary Facilities Serving These Needs

This chapter provides additional details regarding the nation's aeronautic testing needs, given strategic vehicle needs, technical aeronautic considerations, and discussions and surveys of facility users.

Strategic Needs Drive Vehicle Research and Production

Despite the consideration of new concepts, the number of new aerospace vehicles put into production has decreased from historic highs before the 1960s. Figure 2.1 plots our count (shown in Table 2.1) of the number of new vehicle designs reaching first flight per decade. These numbers reinforce what has been generally expressed in the aeronautic community—that fewer vehicles are being put into production today than in the past.

Commercial starts are indeed reducing from about eight per decade in the 1950s to about one per decade in the 1990s and current decade. Military aircraft starts have also slowed (especially when compared with the 1950s), but the nature of the remaining vehicle starts is also changing. Manned military aircraft programs are larger and more complex than their predecessors, and unmanned aircraft are becoming the largest part of the military aircraft starts.

Vehicle Research and Production Result in Test Facilities Needs

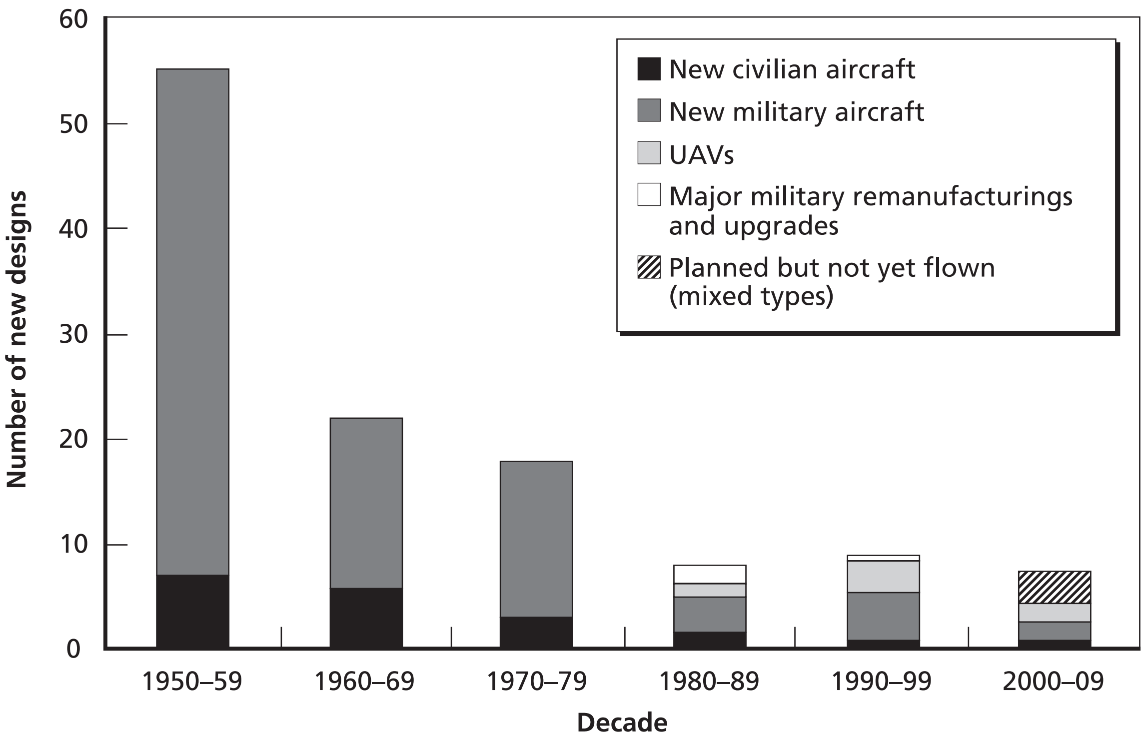
Given the need for strategically important aerospace vehicles, what testing needs result from the research, design, and production of these vehicles?

It is true that some of aeronautics is relatively mature. We are able to consistently manufacture transports and military fighters at amazing levels of efficiency and performance.

Unfortunately, maturity does not imply simple cookbook production, even for these types of vehicles that we have been producing for decades. The field is mature because we know how to exploit empirical physical testing along with computer simulations to generally predict flight performance. Without the facilities for such testing, our maturity will dissolve into nascence.

Furthermore, when we explore newer vehicle concepts such as air-breathing space-access vehicles, UAVs, air-breathing hypersonic missiles, and blended-wing body concepts, our aeronautic and propulsion knowledge is much more limited, placing greater demands on empirical flight simulation facilities to explore and test concepts.

Figure 2.1
Number of New Aircraft Designs Reaching First Flight: 1950–2009 (estimated)



SOURCES: AAI (2000); Airborne Laser (2002); Boeing (1997, 2001, 2002a, 2002b, 2003); Corliss (2003); Drezner and Leonard (2002); Drezner et al. (1992); General Atomics (2002); GlobalSecurity.org (2002a, 2002b); Lockheed Martin (2001, 2003); Lorell and Levaux (1998); Northrop Grumman (2003); Pioneer UAV Web site; Raytheon (1998).
RAND *TR134-2.1*

Technical Needs and Vehicle Types Differ by Sector: NASA, DoD, and Commercial

Technical testing needs differ in the three sectors, even though there are significant overlaps among them (see Figure 2.2).

NASA's national aeronautic role involves it in many areas in common with the DoD and commercial sector. For example, both NASA and the DoD are interested in hypersonic vehicles and propulsion. Also, NASA is actively studying basic problems in emissions and acoustics for commercial vehicles; this area is also of growing interest for military aircraft. NASA's most individual need is in the non-terrestrial aeronautics field because of the agency's space exploration mission. An example of this type of need is parachute testing and other descent systems for Mars Exploration Rover (see Ortiz, 2003). It is interesting to note that NASA has little remaining activity in passenger airliner vehicle research beyond emissions, fuel efficiency, and noise reduction and has interagency (but reduced) relationships in the rotorcraft field.

The DoD has unique needs in the supersonic aircraft field, supersonic and hypersonic missiles, and separation of weapon systems from flying vehicles. Some commercial activity relative to supersonic business jets is being discussed in the commercial sector.

Somewhat surprisingly, we found a large intersection of technical areas where all three sectors share common interest and activities, including subsonic, transonic, and supersonic vehicles; icing; aeroacoustics; propulsion; and access to space.

Table 2.1
New Aircraft Designs Put in Production per Decade (from Figure 2.1)

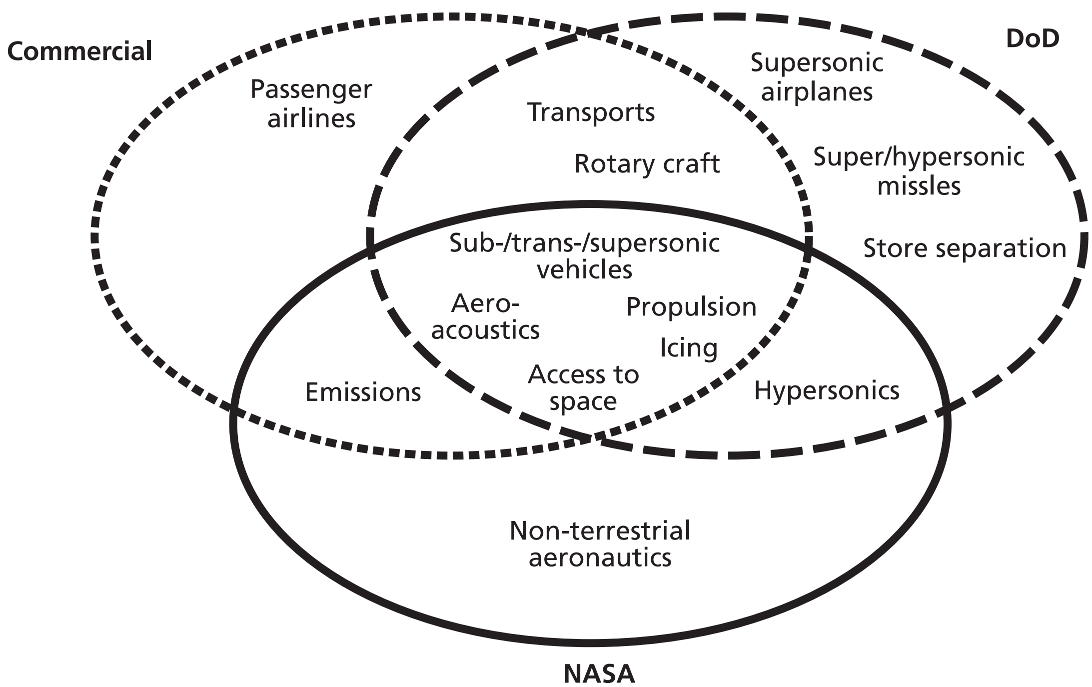
1950–59	1960–69	1970–79	1980–89	1990–99	2000–2009
Boeing 367-80 Dash Eighty	Douglas DC-9	McDonnell Douglas MD-80	McDonnell Douglas MD-11	Boeing 777	X-32
Boeing 707	Douglas DC-8 Super 60	Boeing 767	McDonnell Douglas MD-90	YF-22	X-35
Lockheed Electra	Boeing 737	Boeing 757	F-117	F-22	YAL-1A
Douglas DC-8	Boeing 747	F-14	F-20	YF-23	RQ-7
Convair 880	McDonnell Douglas DC-10	S-3	X-29	X-31	MQ-9
Convair 990	Lockheed L-1011	YA-9	T-46	C-17	X-45
Boeing 727	A-6	YA-10	T-45	F/A-18 E/F	X-47
XP5Y-1	E-2	A-10	B-2	T-6 JPATS	F-35
A2D	SR-71	F-15	RQ-2	Bird of Prey	E-10A
XC-120	XV-4A	F-16	RQ-5	RQ-1	MMA
F4D	X-21	YF-17	KC-135R	RQ-3	Boeing 7E7
F3H	X-19	B-1A	E-6	RQ-4	
X-5	C-141	YC-15	E-8	RQ-6	
B-60	B-70	YC-14		X-36	
B-52	XC-142	AV-8B		AV-8B II+	
A3D	F-111	F/A-18			
X-3	A-7	Have Blue			
S3F	OV-10	Tacit Blue			
X-2	X-22				
F10F	X-26B				
F2Y-1	C-5A				
F-100	X-24				
B-57					
F-102					
R3Y-1					
F-104					
A4D					
B-66					
F11F					
C-130					
F-101					
T-37					
XFY-1					
F8U					
P6M-1					
U-2					
XY-3					
F-105					
X-13					
C-133					
F-107					
B-58					
F-106					
F5D					
X-14					
C-140					
T-2					
F-4					
A-5					
T-39					
T-38					
AO-1					
X-15					
F-5A					
X-18					

NOTE: "Probable first flights" were kept separate in the chart, since they have yet to be realized. They include the F-35, X-46, X-47, MMA, and Boeing 7E7. Chart assumptions were that we only considered U.S. aircraft. The V-22 and XV-15 were considered to be rotorcraft. Designs must have flown (e.g., the A-12 and NASP were not included). No executive jets—civilian or military—were included. Prototypes and production planes count separately (i.e., the X-35 and F-35 were counted as two starts). Only unmanned aerial vehicles (UAVs) with a military designation were counted (e.g., Predator was counted while Gnat 750 was not). Chart data did not include commercial derivatives (737-xxx, 747-xxx, etc.), business jets, turboprops, and general aviation vehicles.

SOURCE: Same as identified in Figure 2.1.

RAND *TR134-table 2.1*

Figure 2.2
Technical Testing Needs and Sector Overlap



RAND *TR134-2.2*

Research, Design, and Production Issues for Vehicles

To help understand how needs change at different stages of an air vehicle's development, Table 2.2 reviews the data and guidance needed at each stage and the testing methodologies available for providing those data and guidance. This summary is applicable where early flight prototype demonstration is not a requirement and could be modified for small vehicles (e.g., UAVs and unmanned combat aerial vehicles [UCAVs]) in which earlier flight testing may be more practical.

The R&D/Preliminary Design and Concept/Configuration Screening Stages. The *R&D and preliminary design stage* is the earliest stage, but it eventually overlaps with the *concept and configuration screening stage*.

In these stages, engineers need data and guidance to construct believable early assessments of critical aerodynamic characteristics (e.g., performance, stability and control [S&C], loads) of candidate concepts and configurations to evaluate feasibility. They also need data and guidance for believable predictions of aerodynamic characteristics to enable effective screening and identification of likely geometries and complexities to achieve desired results. Finally, engineers require data and guidance to identify the risks involved with the concepts being explored.

Methodologies used and required to obtain the needed data and guidance in these stages generally include wind tunnels and CFD. There is an emerging and substantial role for CFD in configuration screening and refinement in some cases (e.g., cruise geometry for

Table 2.2
Typical Data Needed and Testing Methodologies in Air Vehicle Development Stages

R&D/preliminary design Concept/configuration screening	Production: aerodynamics/PI design Production: structural, mechanical, and systems	Refine, validate, document (flight test)
Data and guidance needed: • Concept and configuration feasibility – performance, S&C, loads, etc. • Predictions of aero-characteristicsfor screening • Identification of risks Testing methodologies: CFD: Some configuration screening/refinement – e.g., cruise geometry for transports WT: Most risk areas—flow separation and its implications FT: Too costly and slow	Data and guidance needed: • Establish (i.e., guarantee) vehicle performance, control, and engine/airframe compatibility • Aero loads, S&C simulations (i.e., simulators), various system(s) designs, engine/airframe compatibility, etc. Testing methodologies: CFD: Limited role – Not reliable for many design conditions and situations – Not able to handle very large number of simulations needed WT: Only practical means to acquire the vast amounts of data required in a reasonable time FT: Completely impractical – Cost, schedule, safety, etc.	Data and guidance needed: • Aero- and other characteristics demonstrated, validated, and documented to the satisfaction of customers and/or regulatory agencies – Performance characteristics – S&C characteristics – Engine installation compatibility – Other defined by regulatory agencies, military specifications, etc. Testing methodologies: FT: Only approach acceptable to customers and/or regulatory authorities for validation and documentation

WT: wind tunnel
CFD: computational fluid dynamics
FT: flight testing
PI: propulsion integration
S&C: stability and control

RAND *TR134-table 2.2*

transports). However, facility testing is required to address most risk areas. This typically involves determining when and where the airflow will separate and what happens when it does. Flight testing costs far too much and takes far too long to be considered at this stage for most types of air vehicles, since full-scale, operational vehicles would have to be produced from scratch for each concept and alternative modification under consideration. At least some of these concepts would be unsafe, since it is impossible to predict from theory what may happen in flight conditions (e.g., when Reynolds number [Rn] effects will affect performance and safety).

The Production and Design Stages. Both the production vehicle aerodynamic and propulsion-airframe integration (PAI) design stage and the production vehicle structural, mechanical, and systems development stage begin at the near end of the concept and configuration screening stage, but the former ends earlier.

These stages involve aerodynamic and other data and guidance sufficiently accurate and reliable to establish (i.e., guarantee) vehicle performance, control, and engine/airframe compatibility. Extensive amounts of data are needed for aerodynamic loads, S&C simulations (i.e., simulators), various system(s) designs, engine/airframe compatibility, etc.

The only practical means to acquire the vast amounts of data required in a reasonable period for these stages is via WT/PT facility testing. There is a limited role for current state-of-the-art CFD, since it is not sufficiently reliable for many design conditions and situations and is not able to handle the very large number of simulations needed. For most air vehicles, flight testing is completely impractical for the design process because of the same cost, schedule, and safety issues raised for earlier stages.

Refine, Validate, and Document Stage. Finally, the *refine, validate, and document stage* (or flight-test stage) of the vehicle begins at the end of the production stage. In this stage, aerodynamic and other characteristics need to be demonstrated, validated, and documented to the satisfaction of customers and/or regulatory agencies. These characteristics include performance, S&C, engine installation compatibility, and other performance data required by regulatory agencies and industry standards.

In this stage, flight testing is the only approach acceptable to customers and/or regulatory authorities for validation and documentation, since CFD and WT/PT facility testing are only simulations of actual flight conditions.[1]

Risk Reduction and Sufficient Testing at Each Stage. Not only do the stages of vehicle development have different types of testing needs, but these testing needs also reflect a fundamental lesson learned. Appropriate types and amounts of testing need to be conducted at the appropriate stage of development. Each subsequent stage involves settling on a more static vehicle design. Major changes in later stages are extremely expensive, since significant amounts of engineering and production work will have to be redone. Thus, waiting to uncover and resolve design issues at the later stages runs the risk of incurring significant costs.

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[1] For a recent example, John Muratore, project manager for the X-38/Crew Return Vehicle, was quoted as saying that "in 2001 a vehicle modified from [one] that had flown before with 1,500 hours of wind tunnel time, thousands of CFD runs, tens of thousands of flight control runs, advanced flight controls and we still found something in full-scale flight test that we couldn't find any other way" (Levine, 2001).

Testing Needs Covered a Broad Range of Test Types

Testing needs in the three sectors cover a broad range of test types (see Table 2.3). Some testing involving typical speed regimes or propulsion capabilities can be conducted using generic facilities. However, other testing requires unique or specialized facilities.

Tests that can be performed in broad-purpose facilities include those measuring the force and moment loads on a vehicle at different positions and configurations; control of air flow and understanding where flows separate from the vehicle; the effects of exhaust on vehicle performance, stability, control, and noise; interactions between airframe and propulsion components; and standard direct-connect propulsion tests where the airflow is fed directly through the engine.

Specific needs within each type of test have demands that determine the types of facilities in which the tests can be performed. These characteristics include size requirements for model accommodation, needs for technical support and test type for R&D versus needs for high-throughput T&E that focuses more on how many data-sequenced polars can be tested per hour, and cost constraints.

When test characteristics move beyond what a standard test facility can provide, specialty facilities must be employed. These specialty tests involve very high Rn; exhaust effects (performance, stability, control, noise); airframe/propulsion interactions (inlet, exhaust); acoustic and sonic boom measurements; aerothermodynamic measurements; flutter and aeroelastic effects; recovery from vehicle spin; effects of store (weapon) separation from the vehicle; and icing effects.

Because vehicle performance and complexity are increasing over time, testing demands are expanding and taxing the capabilities of existing facilities and techniques. Vehicle designers are also placing increased emphasis on the economy, efficiency, and quality of the testing performed, further taxing the ability of test facilities and techniques. Testing

Table 2.3
Generic and Specialty Facility Tests

Generic Facility Tests[a]
Force and moment loads
Flow control and separation
Direct-connect propulsion
Specialty Facility Tests
Very high Rn
Exhaust effects (performance, stability, control, noise)
Propulsion/airframe interactions (inlet, exhaust)
Acoustics (especially subsonic)
Aerothermodynamics (hypersonic)
Aeroelasticity (dynamics; transonic flutter)
Spin recovery (subsonic)
Low turbulence (especially subsonic)
Store separation (transonic)
Icing (subsonic)

[a]Denotes subsonic through hypersonic; propulsion; size requirements; R&D vs. T&E; costs; etc.

needs, therefore, are not a simple matter of execution in a tunnel of the appropriate speed. Aeronautic vehicles require a wide range of tests that are met with a range of test facilities and techniques.

Specific Testing Needs Today

Testing needs across all three sectors can be conveniently described by their speed regimes. In Table 2.4, we outline some of the more important and challenging subsonic and transonic testing needs. These tests are often needed for commercial and military transports, but they also include other vehicle types and special aeronautic challenges.

Propulsion testing from R&D to T&E is often driven by improving efficiency, noise, and emissions of both commercial and military transport vehicles. Transonic drag measurements inform designs to increase the efficiency of the vehicle, and complex subsonic flow measurements inform designs to reduce noise emissions.

Table 2.4
Selected Testing Needs and Activities by Speed Regime

Subsonic and Transonic Systems[a]
Propulsion RDT&E (efficiency, noise, emissions)
Transonic drag measurements (efficiency)
Complex subsonic flow (noise)
Smart rotorcraft blades
Blown wings for SSTOL
VTOL boundary effects
Ground-effects transport airplane (Boeing "Pelican")
Wake testing
Icing T&E (freezing rain)
Aeroelastic testing (transonic flutter)
Mach 0.98 testing (far term; tunnel wall reflections)
UAVs (near term)
Personal air vehicles (far term)
Supersonic Systems[b]
Propulsion T&E (performance)
High angle-of-attack/high-G effects
Store-separation dynamics
Reduced boom
Laminar flow (drag): Quiet enough?
Aeroelastic and aerothermodynamics
Hypersonic Systems[c]
Aerodynamics testing Mach 5–20 for 2nd- to 3rd-generation reusable launch vehicle (RLV) and orbital space plane
Flow over control surfaces/windows, shroud separation, materials and structures
Aeroelastic and aerothermodynamics
Propulsion
Hypersonic propulsion R&D (air-breathing scramjet feasibility)
Integrated airframe/engine concepts
Combined-cycle engines
All-electric propulsion (far term; feasibility)

[a] For example, commercial/military transports, tactical AC, UCAVs, rotorcraft, and missiles.
[b] For example, fighters, UCAVs, missiles, and supersonic business jets.
[c] For example, tactical missiles, space launch, and aerospace planes.

Other testing needs address a range of vehicles and issues. Smart rotorcraft blades change their angle as they rotate through their circular path to improve lift and reduce noise. Researchers are looking at techniques such as blown wings to control the flow of air over wings with the goal of developing super-short takeoff and landing (SSTOL) vehicles. Vertical takeoff and landing (VTOL) vehicles, for example, have boundary-effect problems that interfere with liftoff. Icing continues to be a dangerous problem for all types of aeronautic vehicles, and managers of T&E facilities need to expand their facilities' capabilities to support the analysis of larger precipitants such as freezing rain. Vehicle wakes limit the landing and takeoff spacing at airports, and wake testing remains a challenge. R&D for UAVs, including UCAVs, has accelerated in recent years. New concepts for much larger military transports are exploring wing-in-ground effects for efficient, near-surface cruise. Concepts for near–Mach 1.0 cruising (such as Boeing's recently canceled "Sonic Cruiser" concept) will need to address test challenges such as tunnel wall reflections that are the worst at Mach 1.0. Finally, far-term concepts of personal air vehicles involve some radical concepts that will challenge testing capabilities.

Military fighters, UCAVs, and missiles along with some future testing for the orbital space plane during reentry dominate the supersonic regime. Here the propulsion development focuses on performance and is most prevalent at the T&E level. High-angle-of-attack and high-G effects are common concerns, given that they generate complex separated flow onsets and transitions. New weapons typically occur more often than new vehicles, generating the need to understand how these "stores" separate from the vehicle and affect its aerodynamic flows and stability. Research continues on how to reduce sonic booms, especially for military aircraft, given their environmental effects on populated areas. R&D also continues on how to both control laminar flow and configure wings to retain laminar flow (or at least non-separated flow) as long as possible to reduce drag. An issue with laminar flow testing is whether the tunnel's flow is "quiet" (i.e., smooth) enough to simulate flight conditions properly. As with all flight regimes, aeroelastic and aerothermodynamic effects are test topics that require specialty test facilities.

Tactical missile R&D as well as space vehicles dominate the hypersonic regime. Aerodynamic testing for these vehicles ranges from Mach 5–20, especially for the second- and third-generation RLV concepts and the orbital space plane that glides back to earth. Topics of concern include hypersonic flow over control surfaces and windows, missile shroud separations, and testing for new materials and structures.

Finally, the propulsion area has active R&D in developing viable air-breathing ramjet and scramjet engines with sufficient thrust for payloads of interest in hypersonic missiles and transports. Another concept is the integration of engines into the airframe—not just for ramjets and scramjets but for conventional engines to reduce vehicular drag. Other R&D trends include combined-cycle engines and the feasibility of all-electric propulsion in the future.

Flow Physics Situations and Issues for Aerospace Testing

Table 2.5 lists the controlling flow physics situations and issues necessary to take into account when establishing necessary and appropriate testing requirements. It also specifies the vehicle flight characteristics that are affected by each flow physics situation, thus helping to exemplify the importance of each of these situations in more real-world terms. For

Table 2.5
Controlling Flow Physics Situations and Issues for Air Vehicles

Flow Physics Situations and Issues	Vehicle Flight Characteristics Affected
Boundary layer transition status and location[a]	
• Natural transition • Transition fixing (viscous simulation) • Delaying transition (LFC) • Laminar vs. turbulent boundary layer separations • Surface condition effects • WT turbulence levels and noise have major effect • Relaminarization observed on high-lift systems in flight	• Drag • Maximum lift • S&C characteristics • Buffet onset • LFC effectiveness • Aerodynamic heating • Heat transfer effects
Turbulent boundary layer *attached* flows[b]	
• Rn effects: –skin friction levels –displacement thickness –surface irregularities	• Drag (skin friction, form, and interference) • "Linear" S&C characteristics
Viscous flow separation onset and progression[a]	
• Leading-edge separations • Trailing-edge separations • Shockwave–boundary layer interactions • Juncture flow separations • Off-body flow reversals • Laminar vs. turbulent boundary layer separations • Reynolds number effects • Separation onset control/delay	• Maximum lift capability • Drag • "Nonlinear" S&C characteristics • Buffet onset and progression characteristics • Flow control concept effectiveness • Spin departure? • Flutter
Fully separated flows[a]	
• Base flows • Cavities • Wakes behind bluff bodies • Post separation onset/progression	• Noise sources • Post-stall pitching characteristics • Post-buffet onset/progression pitch characteristics • Drag • Spin
Flow merging and mixing[a]	
• Multielement high-lift system wakes and viscous layers • Propulsive jet interactions	• Maximum lift capability • Interference drag • S&C characteristics
Vortex phenomena[a]	
• Vortex/viscous interactions for flow control • Wake vortex characteristics • Interactions with downstream components • Surface-edge effects • Surface-sweep effects	• Maximum lift capability • Buffet onset levels and ensuing pitch characteristics • Aircraft spacing at takeoff and landing • Airframe noise levels • "Nonlinear" S&C characteristics • Undesirable unsteady flows (e.g., tail buffeting) • Rotorcraft
Shockwave characteristics[b]	
• Off-body characteristics • Bodies in proximity • Pressure rise and turbulence amplification through shocks • Shock position/movement	• Sonic boom for supersonic vehicles • Aero meeting • Flow control concepts for reducing shockwave drag
Ice accretion characteristics and effects[a]	
• Impingement limits vs. droplet size • Ice accretions typically irregularly shaped and very rough • Computed shapes typically do not look like measured ones • Wide variety of accretions possible • Rn and heat transfer effects	• Maximum lift/stall margin • Drag • S&C characteristics (including tail stall) • Flight safety

[a]*Not* handled well by CFD.
[b]Handled well by CFD.

example, drag (listed for most situations) affects the range of a vehicle, the required engine performance, amount of fuel storage and weight, fuel efficiency, etc. Maximum lift affects the size of runways needed, the cargo weight capacity of an aircraft, cruise performance, etc.

Note that CFD can handle only two of the eight flow physics situations and issues well: turbulent boundary layer *attached* flows and shockwave characteristics. The other six flow physics situations must be studies with WT/PT facility simulations or flight testing.

Appendixes D and E provide additional technical insights into the first two flow physics situations: boundary-layer transition status and location, and turbulent boundary layer attached flows.

Hypersonic Propulsion Integration Needs

Hypersonic propulsion integration presents many significant challenges. There has been a recent upsurge in hypersonic propulsion research (e.g., on ramjets and scramjets) pursuing the goal of providing air-breathing hypersonic vehicles for access to space and for missiles to reduce the amount of oxygen carried by hypersonic vehicles, resulting in lighter and smaller vehicles. This research could result in a change in the way of designing an aircraft or missile and has the largest advantage for space access. The possibility of viable air-breathing hypersonic propulsion has also resulted in the recent increased utilization and need for hypersonic WTs.

Unfortunately, air-breathing hypersonic engine concepts have merely achieved positive thrust capabilities in limited circumstances. Questions regarding combustion initiation, sustained combustion, significant thrust for usable payloads, and combustion chemistry will require continued R&D leveraging a full range of ground test facilities.

The importance of non-vitiated air in test facilities is an unresolved debate within the hypersonic propulsion community. Air must be heated to achieve flight temperatures in the test cell, but most facilities use combustion processes to heat the air, leaving by-products and changing the gas composition of the flow into the test engines. These nonrealistic by-products and gas mixtures may interfere with the hypersonic propulsion in ramjets and scramjets. To resolve this issue, non-vitiated facilities are needed to compare with the engine performance in vitiated facilities.

Insights into the Hypersonic Propulsion Integration Challenge Resulting from the National Aerospace Plane Program. We found the following observations from the Air Force Systems Command (ASC) responses to the hypersonic propulsion integration questionnaire particularly enlightening and relevant. These lessons were learned from the country's National Aerospace Plane (NASP) effort.

> Our experience and comments come primarily from the NASP program since it was refurbished, upgraded and/or built and tested in every applicable facility existing in the country at that time. Our comments are also based on our recent involvements in the AFRL HyTech, DARPA [Defense Advanced Research Projects Agency] ARRMD (Waverider and DCR concepts), gun-launched projects (at LLNL and GASL/AEDC), and miscellaneous magnetohydrodynamic (MHD) and magnetogasdynamic (MGD) propulsion programs (*à la* the Russian "Ajaks" concept).
>
> Space access vehicle (SAV) air-breathing propulsion testing requirements dominate testing requirements for all other applications. They cover the widest range of Mach numbers (0 to about Mach 20) and require the largest scale due to the size of those vehicles. Only potential missile configurations that may want to operate at very high

dynamic pressures as they power dive onto a target are likely to have a requirement outside of the SAV flight envelope. Virtually all other test requirements, such as those for a Mach 8 hydrocarbon or Mach 10 hydrogen powered missile, or a Mach 7 cruise aircraft, are subsets of the SAV trajectory, either in scale or simulation conditions.

Development of an air-breathing SAV will require a massive undertaking in propulsion and propulsion integration testing, regardless of the propulsion system type (Turbine-Based-Combined-Cycle or Rocket-Based-Combined-Cycle) or number of stages (two-stage-to-orbit or single-stage-to-orbit). Virtually all types of testing will be required, from focused basic physics and chemistry experiments in cells like the Stanford's shock tube and the CALTECH T-5 piston-driven shock tunnel to component tests in the GASL or NASA direct connect combustor and AEDC Tunnel-9 for large-scale, high-speed inlet tests, and including integrated large-scale engine tests in facilities like AEDC APTU and ASTF (C-cells), NASA Langley's 8-foot HTT, and the NASA Ames 16-inch and Army Large-Energy National Shock (LENS) shock tunnels. In addition, propulsion-vehicle integration experiments will be required in facilities like the AEDC von Karmen tunnels for powered effects and propulsion force-and-moment testing. A snapshot of the main NASP test facilities (circa 1991) is included in Figure 2.3. Many more facilities were used in that program, some to a great extent for component testing in particular but are not shown here. *Building a SAV will require all of these types of facilities and probably innovative low-cost flight test demonstrators as well.*

Due to the extreme difficulty in simulating the flight environment and chemistry for air-breathing engines of any scale above about Mach 4, it is *unlikely that a facility will be built which can test engine performance, control, operability, and structural durability of these engines*. Therefore it is *imperative* that any ground-based high-speed air-breathing propulsion development program contain the following 3 elements:

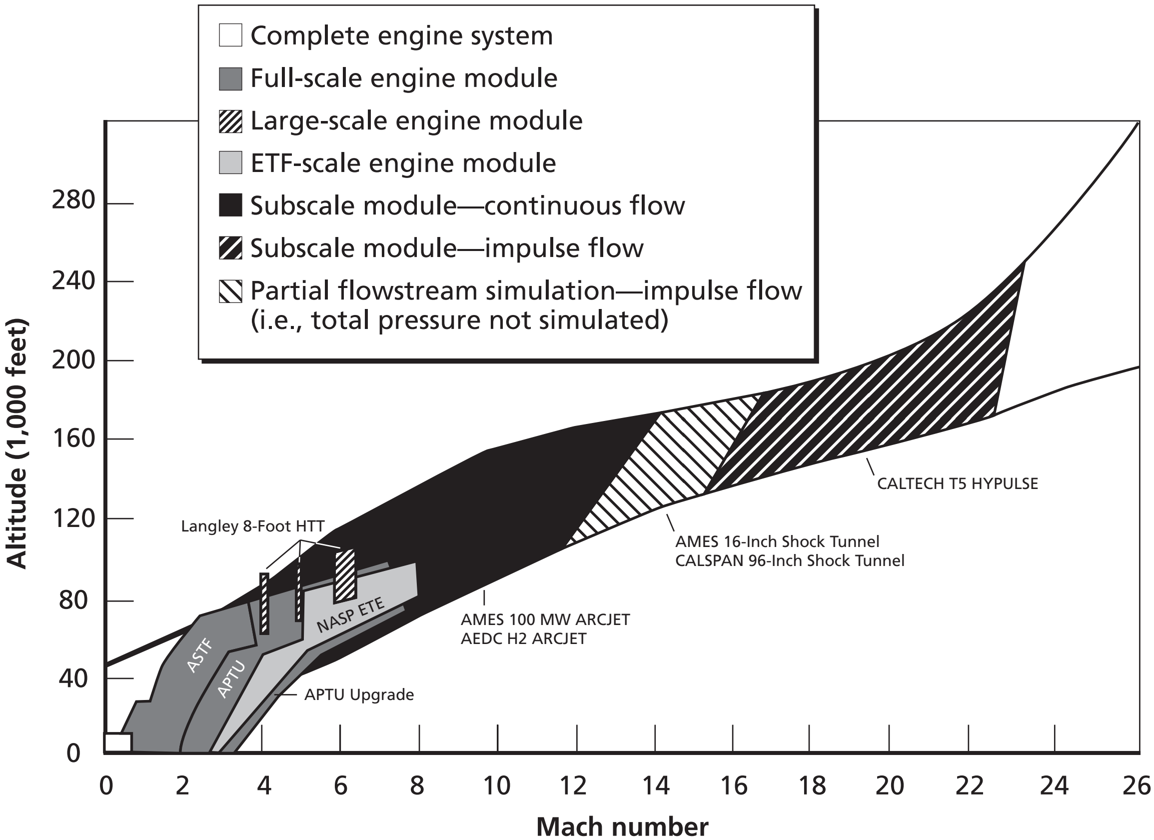
i) Development of new and emerging robust non-intrusive instrumentation that can make key measurements within the flowfield of components and engines made up of actively-cooled panels that do not offer optical access and that can be tested in the harsh and dirty environment of our larger, non-laboratory-type test facilities.

ii) Multiple test facilities of differing attributes with overlapping capabilities such as scale, Mach number, enthalpy, total pressure, test-gas composition, and test time. Careful overlap of tests and configurations among different facilities across the wide range of Mach numbers they must operate in is the only way to verify that components and engines will function as predicted and designed within acceptable uncertainty ranges. Without full simulation capabilities, non-availability of a wide range of facilities will directly increase the risk in a development program.

iii) Calibration of design and analysis codes (1D, 2D and 3D, to include but not limited to CFD) to detailed data generated throughout the range of facilities and using the non-intrusive instrumentation described above.

This approach was used to great effect during the last few years of the NASP program and was responsible for very significant advances in all 3 areas, details of which are very closely held.

Figure 2.3
Main Test Facilities Used for the NASP Circa 1991



SOURCE: Air Force Systems Command.
RAND *TR134-2.3*

Identifiable Needs in Existing Test Plans

In December 2002, respondents to our survey were able to quantify some (but in no way all) of their future testing needs. Most of the quantified needs were from users' existing testing plans; when no plans existed, most users responded with very qualitative insights into their possible future testing needs or, in some cases, a very rough order of magnitude of total testing hours per year.

We received responses from the organizations and programs listed in Table 2.6. Of the two current major fighter aircraft production programs—the Joint Strike Fighter (JSF) and the F-22—JSF data were included, but we could not include data on the F-22, since the F-22 Systems Program Office was not able to respond to our questionnaire owing to the press of demands by Congress and the DoD on its program status at the time of our study.

We categorized the test hours by speed regimes and propulsion testing and rolled them up to provide a national perspective, albeit an incomplete one, as shown in Figure 2.4.

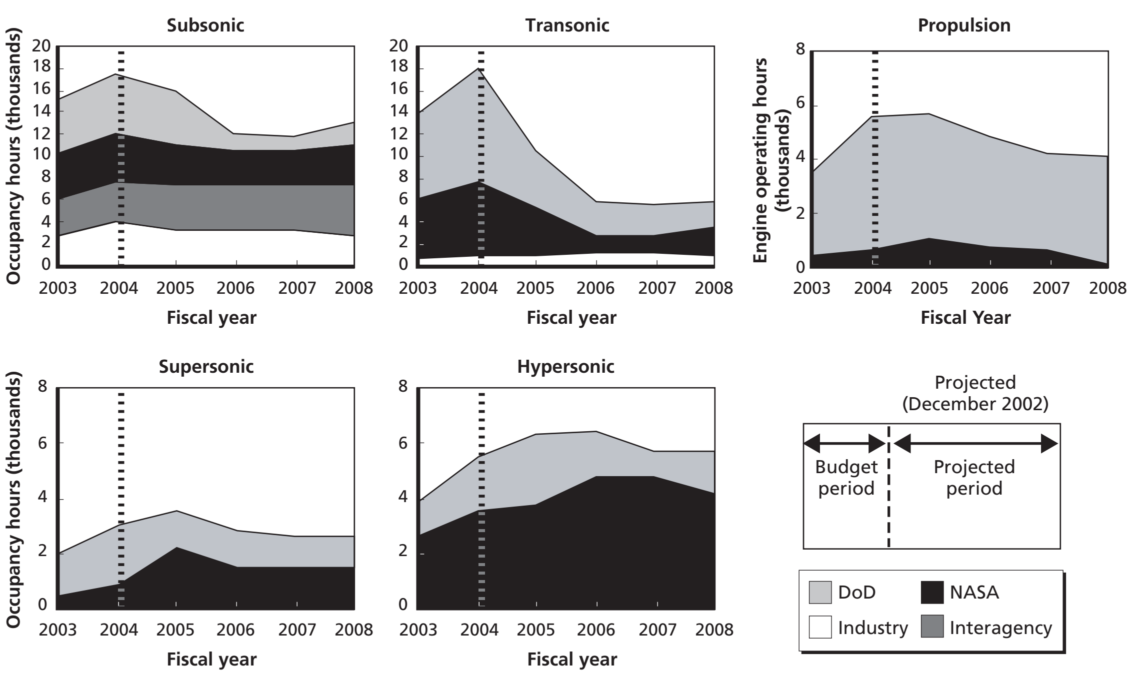
Note that these numbers can show some future trends, but given the uncertainties even in existing programs as to what their test plans will be in out-years, these numbers cannot be relied upon to forecast future utilization or to make strategic decisions as to what test

Table 2.6
Organizations Contacted (December 2002) for Quantitative Estimates of Future Testing Needed

NASA		Department of Defense	
Aviation Safety • AVST: –QAT –AsCOT –Morphing –SLMFST –Survivability –ACE –HyperX –RACR –TCAT	Space Transportation • ISTAR • NGSL • Beamed Power • TBCC • RTA	Army • Redstone • Picattiny Navy • NAVAIR –Pax River –China Lake Missile Defense Agency	Air Force • Headquarters/Air Staff • Air Force Research Laboratory –Seek Eagle DARPA • UCAR • HyFly Joint Strike Fighter
Industry		**Interagency/International**	
Boeing[a] Northrop Grumman (ROM) Bell Cessna Gulfstream[b] Raytheon[b] General Electric Pratt & Whitney Rolls-Royce[c] Williams		NASA/Army Rotorcraft Division Space Launch Initiative (SLI) • Next Generation Launch Technology • Orbital Space Plane National Aerospace Initiative (NAI)[c] • Hypersonics • Space Access • Space Technology	

[a]ATT response only.
[b]Qualitative response only.
[c]No response.

Figure 2.4
Respondents' Identifiable Testing Needs Through 2008



RAND *TR134-2.4*

facilities will be needed. For example, the Orbital Space Plane program's response was that their requirements have yet to be determined. Some funded DARPA programs did not even have their contractors engaged and therefore could not specify their test plans.

In some sense, these aggregated data on utilization (test hours) are a misleading metric because they do not capture the value of a facility to a particular program or set of programs. Several programs require unique testing capabilities that are critical to the successful implementation of the program. As a result, tunnel availability is more important and a better metric for value than is use. As an example, the Missile Defense Agency (MDA) is the sole user of the AEDC's Tunnel #9, which therefore caters to MDA's unique testing needs. It is critical to the mission of MDA that this capability remain available, regardless of actual or projected utilization. We discuss additional insights on assessing capabilities in the context of needs in Chapter Three.

Observations from Responses to the Utilization Forecast. WT/PT facilities are needed for research and program risk-reduction strategies. Specialty needs go beyond simple speed regime characterizations, and utilization remains highly variable.

Such forecasts help to anticipate test type needs and gross levels, but programs cannot always estimate needs; policy and market changes will affect demand; technological breakthroughs that cannot be predicted will cause demand "bubbles"; and there are some past examples of misestimated projected needs.

Complementary Testing Approaches and Their Effect on Test Facilities: Computational Fluid Dynamics and Flight Testing

CFD Has Reduced Some WT/PT Facility Testing Needs, but Only in Specific Areas

CFD involves using computers to simulate fluid dynamic situations and configurations during research and vehicle design. "Reverse design" techniques can also be used to ask the CFD code to produce an aerodynamic design that meets specified performance parameters—i.e., the "reverse" of giving the code the design and asking it to calculate the performance data.

CFD has made inroads in reducing *some* empirical test simulation needs, but the technology will not eliminate the need for test facilities for the foreseeable future.[2] Estimates of the time frame for computer simulation to be capable of fully replacing WT/PT facility testing are on the order of decades.[3] This estimate neither diminishes the importance of CFD nor the need for continued investment in simulation technology, but it does put the capability in proper perspective as a *complementary* resource to ground test facilities and flight testing.[4] To that end, CFD has proven an excellent tool for preliminary design configuration screening (simulation of conventional aircraft at cruise condition has allowed up to 50 per-

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[2] See, for example, Rahaim et al. (2003) for a good overview of the status and future plans for CFD, and Oberkampf and Blottner (1998) for a broad survey-level discussion of the ways in which CFD can encounter inaccuracies.

[3] The *DoD Aeronautical Test Facilities Assessment* (1997) reported that "extensive use of CFD to replace wind tunnel data [is] 20 to 40 years away," while other expert assessments contended that this anticipated time frame is an underestimation.

[4] See Giunta, Wojtkiewicz, and Eldred (2003) for modern design-of-experiment methods for CFD codes. See also Streett (2003) and Streett et al. (2003) for good examples of experiments that blend CFD and other experimental techniques.

cent reductions in physical testing at the screening stage[5]). For an extremely limited set of cases, it is even possible to make predictions more accurately than with WT/PT facilities.[6]

However, validated capability is limited to these relatively simple flow conditions. CFD is not yet considered reliable for predicting the characteristics of the complex separated flows that dominate many critical design points for an aircraft. Continued investment in CFD should result in steady advancements in the envelope of validated simulation capabilities, but the validation process itself will require many precise WT/PT facility experiments.[7] Ironic as it may be, we cannot hope to eventually replace the WT/PT facility as a testing facility without maintaining high-quality WT/PT testing facilities during CFD development.

Even when the codes are reliable, CFD methods are not able to generate quickly enough the vast amounts of aerodynamic data needed in the production design process. Thus, CFD has the greatest effect on reducing gross testing hours in preliminary design studies, although the technology is used to explore some questions during production or even problems uncovered during flight testing.

Flight Testing Remains Unfeasible for Design Data Needs for Most Vehicles

Flight testing plays a dominant role during final refinement and validation of a production aircraft (the fifth stage in Table 2.2), but except for small vehicles for which multiple, full-scale, flight-capable vehicle concepts can be quickly and relatively inexpensively produced (or for some selected vehicles for which we cannot economically develop a test simulation facility), flight testing will not replace WT/PT facility testing for research, design, and early production stages. As noted above, waiting to uncover and resolve design issues at the later flight testing stage runs the risk of incurring added costs.

For example, one user noted that flutter models of essentially every high-performance military aircraft for the past 50 years have been tested in the Langley Transonic Dynamics Tunnel (TDT) except for one: the F/A-18A. This postponed the discovery of the following aeroelastic problems with the F/A-18A until flight testing:

- limit cycle oscillations of the wing when certain external stores are carried
- vertical tail buffet and horizontal tail buffet
- wing leading flap divergence
- aileron reversal well inside the flight envelope
- wing aeroelastic loads.

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[5] Screening-stage reductions were cited by multiple industry design experts in response to our survey questions. See also Beach and Bolino (1994), Crook (2002), and Smith (2004) for additional discussions on the effects of CFD testing on WT/PT facility testing hours. However, the benefits of using CFD for initial screening and to improve testing efficiency do not necessarily indicate a reduction in overall WT/PT facility testing hours. Rather, a complementary CFD program presents an opportunity to shift more testing resources from preliminary explorations to final optimization. Respondents made it very clear that decisions on quantity of testing are primarily budget driven and that they will test as much as they can afford to address the range of technical concerns and reduce important risks when possible.

[6] See Oberkampf and Aeschliman (1992) and Walker and Oberkampf (1992).

[7] Validations challenges include knowing a great deal more about the flow field in the tunnel than at the surface of the model, significant instrumentation, tests with multiple models sizes, and significant funding. See, for example, Aeschliman and Oberkampf (1998).

All these problems were related to the aeroelastic (highly flexible) airframe of the F/A-18A. Resolving these problems during the late flight-test stage was very expensive (personal communication).

Factors Influencing Actual Facility Utilizations

Despite the strategic testing needs outlined above, actual facility utilizations will vary from year to year (or even decade to decade) as a result of program starts and ends (including NASA research programs as well as production vehicle programs). Many in the user community (NASA, the DoD, and industry) said that R&D budgets have been declining in recent years, especially when considering the recent cancellations of large efforts such as the High-Speed Civil Transport (HSCT) and NASP. However, current upswings in space-access, hypersonic missile, UAV, and UCAV efforts will result in utilization upswings in facilities related to those vehicle classes.

Engineers and program managers alike also cited a decline in budgetary resources for testing as a factor in recent test reduction trends. As mentioned above, CFD has been able to reduce testing (especially for early configuration screening) and has leveled the growth of testing time per vehicle, but it will not eliminate testing.

The time interval between new production launches has been significantly lengthened (recall Figure 2.1 and Table 2.1). There have been many proposed concept vehicles that were never produced (e.g., the 747x, HSCT, Sonic Cruiser), which never generated the need for the large amounts of WT/PT facility testing required at production stages.

Beginning with the production of the JSF, government test facilities will no longer provided as government-furnished equipment. The contractor is given funding for testing and is generally free to select what test facilities (i.e., NASA, DoD, industry, private, and/or foreign) are most appropriate based on capability, cost, and schedule. In one example, according to our survey responses, European facilities such as DNW (German-Dutch Wind Tunnels) have been found to be superior to U.S. facilities for short takeoff and vertical landing (STOVL) investigations, driving use toward the foreign DNW tunnel and away from U.S. facilities. For DoD work, though, there remains some level of customer monitoring to determine which facilities are most appropriate to minimize risk. This trend may reduce actual domestic utilizations in certain situations (most notably the Ames 12-Foot Pressure Wind Tunnel when compared with the foreign QinetiQ 5-Metre, as discussed later), but the strategic need for domestic capability remains unless the United States makes a conscious decision to rely on foreign facilities for test capabilities vital to important U.S. aeronautic vehicle RDT&E.

NASA's Primary WT/PT Facilities for Nation's Needs

Tables 2.7–2.12 map NASA's WT/PT facilities against the types of facilities needed by the nation, identifying the primary NASA facility (when available) for each type of needed facility and NASA facilities considered backups to these primary facilities. Note that some capabilities are only available at facilities outside NASA's infrastructure. We identified gaps when no NASA facility existed to serve a national need and listed related facilities in each category that have been closed by NASA in the past.

Table 2.7
NASA's Primary Subsonic WTs

	Needed?	Primary NASA Facility	Major Investments Needed	Related Existing Facilities	Related Closed, Sold, or Abandoned NASA Facilities
General-Purpose					
Large, high Rn	Yes	Ames 12-Foot[a]	Systems software, tunnel reliability	Foreign 5M and F1	
Small, high Rn	No	N/A		None	
Large, atmospheric	Yes	Langley 14×22-Foot	Moving ground plane	Langley 12-Foot, academia, private industry	
Small, atmospheric	No	N/A		Academia	
Special-Purpose					
Propulsion simulation	Yes	Glenn 9×15-Foot, Langley NFAC		AEDC	
Very large, atmospheric (rotorcraft)	Yes	NFAC	Spare blades		Langley 30×60-Foot
Icing	Yes	Glenn IRT	Freezing rain	Italy, Boeing	
Large-field acoustics	Yes	NFAC 40×80-Foot		None	
Near-field acoustics	Yes	Langley 14×22-Foot, Glenn 9×15-Foot		Boeing; DNW	Ames 7×10-Foot
Spin	Yes	Langley Spin		AFRL 12-Foot Vertical, Canadian 5M VWT[b]	
Low-turbulence	Yes	Langley LTPT		No	
Dynamics	Yes	Langley 14×22-Foot		Industry	

[a]Currently needed for space vehicles. Investigate investments for AEDC 16S/T to run at high-Rn subsonic speeds to fill this role.
[b]Additional analysis is required to determine what dynamics can be modeled in the AFRL 12-Foot Vertical Tunnel and the Canadian 5-Meter Vertical Wind Tunnel compared with the Langley 20-Foot Vertical Spin Tunnel.

Table 2.8
NASA's Primary Transonic WTs

	Needed?	Primary NASA Facility	Major Investments Needed	Related Existing Facilities	Related Closed, Sold, or Abandoned NASA Facilities
General-Purpose					
Large, high Rn	Yes	Ames 11-Foot[a]		AEDC 16T	Langley 8-Foot TPT, Ames 14-Foot
Medium, high Rn	Yes	Langley NTF	Model dynamics; productivity	ETW (Germany)	
Small, high Rn	No	N/A		AEDC 4-Foot	
Large, atmospheric	Yes	Ames 11-Foot[a]		Langley 16TT, AEDC 16T	
Medium, atmospheric	Yes	Langley NTF	Model dynamics; productivity		Langley 16-Inch, Langley 6×28-Inch
Small, atmospheric	No	N/A		AEDC 4-Foot	
Special-Purpose					
Very-high Rn	Yes	Langley NTF	Model dynamics; productivity	ETW (Germany)	
Propulsion simulation	Yes	Glenn 8×6-Foot	Force measurement capability	Langley 16TT, AEDC 16T	
Dynamics/flutter	Yes	Langley TDT	Age?		

[a]If agreements can be made regarding cost and availability of the AEDC 16T, then the 11-Foot could be replaced by the AEDC 16T in the future.

Table 2.9
NASA's Primary Supersonic WTs

	Needed?	Primary NASA Facility	Major Investments Needed	Related Existing Facilities	Related Closed, Sold, or Abandoned NASA Facilities
General-Purpose					
Large, high Rn	Yes	(Gap)		AEDC 16S[a]	
Medium, high Rn	Yes	Ames 9×7-Foot	Complete 8×7-Foot data acquisition and controls	AEDC, private industry	Ames 8×7-Foot,[b] Ames 6×6-Foot
Small, high Rn	Yes	Langley UPWT 4-Foot		AEDC, private industry	
Special-Purpose					
Propulsion simulation	Yes	Glenn 10×10-Foot		AEDC 16S	

[a]If agreements can be made regarding cost and availability of the AEDC 16S, then the AEDC 16S could be considered part of the nation's minimum set in the future.
[b]According to Ames, it would require about $8 million and two years for computer control hardware and software to reactivate the 8×7-Foot.

Table 2.10
NASA's Primary Hypersonic WTs

	Needed?	Primary NASA Facility	Major Investments Needed	Related Existing Facilities	Related Closed, Sold, or Abandoned NASA Facilities
General-Purpose					
Low Mach	Yes	Langley 20-Inch M6 Air		AEDC VKF B	Langley 12-Inch Mach 6 High Rn
Moderate Mach	Yes	Langley 31-Inch M10 Air		AEDC VKF C	Langley 18-Inch Mach 8 Quiet Tunnel
High Mach	Yes	(gap)		Industry	Langley 22-Inch Mach 20 Helium, Langley 20-Inch Mach 17 Nitrogen, Langley 60-Inch Mach 18 Helium
Special-Purpose					
Real gas effects	Yes	Langley 20-Inch M6 CF4		None	

Table 2.11
NASA's Primary Hypersonic Propulsion Integration Test Facilities

	Needed?	Primary NASA Facility	Major Investments Needed	Related Existing Facilities	Related Closed, Sold, or Abandoned NASA Facilities
Ramjet/scramjet	Yes	Langley 8-Foot HTT, Arc Scramjet, Combustion Scramjet, SS Combustion, 15-Inch M6 HTT, and NASA/GASL HYPULSE		AEDC APTU	

Table 2.11—Continued

	Needed?	Primary NASA Facility	Major Investments Needed	Related Existing Facilities	Related Closed, Sold, or Abandoned NASA Facilities
Integrated engine tests	Yes	Reactivate Ames 16-Inch, or gap			Ames 16-Inch Shock (mothballed)
Longer-duration testing	Yes	Reactivate Ames direct-connect facility, or gap			Ames Direct-Connect (mothballed)
Non-vitiated	Yes	Glenn HTF			
High Mach	Yes	(Gap: use industry)		Industry	

Table 2.12
NASA's Primary Direct-Connect Propulsion Test Facilities

	Needed?	Primary NASA Facility	Major Investments Needed	Related Existing Facilities	Related Closed, Sold, or Abandoned NASA Facilities
Large engine and component	No	N/A		AEDC ASTF	
Medium engine and component	Yes	Glenn PSL-3,4			
Small engine and component	Yes	Glenn ECRL 2b			

On Facilities as Backups

Facility managers and users alike expressed skepticism regarding the concept of retaining facilities solely as "backups" if they are not used to some reasonable level (e.g., conduct a few tests a year) to maintain the workforce's skills. Thus, backup facilities need a minimal level of utilization to maintain their capabilities.

It should also be noted that facilities often have unique mixes of capabilities. Thus, a facility may be an effective backup for another facility but only for certain uses. Also, a set of various facilities might collectively back up the capabilities of an important facility.

Upgrades and New Facilities Needed

Across all the test facility types, some emerging views of needed improvements and unmet needs have emerged.

A number of potential users expressed concerns about the aging infrastructure of NASA (and AEDC) test facilities. There was strong advocacy for selecting a minimum set of facilities that support national interests and that are well preserved, maintained, and upgraded to meet evolving needs. There was also strong emphasis placed on retaining well-trained, motivated, and knowledgeable facility operators and engineers.

Needed Improvements to Conventional WT/PT Facilities

The user community respondents presented some areas where they felt improvements were needed to conventional WT/PT facilities. Some respondents expressed a desire for improving capabilities for power simulation for tactical aircraft and rotorcraft. Others advocated improving the flow quality (i.e., quieting) WT/PT facility flows for noise studies and laminar flows for UAVs and UCAVs. Improved productivity is needed for the National Transonic Facility (NTF) (both at cryogenic temperatures and during atmospheric tests) as well as a means of avoiding and eliminating excessive model dynamics at cryogenic temperatures. Also, selected primary transonic facilities should be upgraded to raise their speed range to 1.5–1.6 Mach, and the AEDC 16-Foot Supersonic Wind Tunnel (16S) should be upgraded to regain its original Mach 4.0 capability.

Interestingly, no respondent suggested spending the more than $100 million to make the Ames 12-Foot "acceptable" to the commercial transport industry (Boeing). It could not be justified in light of very uncertain and unlikely future utilization as well as the ready availability of the superior QinetiQ 5M in the United Kingdom.

The feasibility of using larger, high-Rn AEDC transonic or supersonic WTs at subsonic speeds to augment U.S. subsonic testing capabilities should be studied. For example, upgrading the AEDC 16T or 16S to provide three-atmosphere testing at subsonic speeds is particularly appealing. AEDC has conducted some preliminary studies in this regard; this research should be reviewed and expanded if promising.

New Facilities?

As for needed new facilities, serious research challenges in hypersonic air-breathing propulsion may require new facilities and testing approaches for breakthroughs. However, research should be done first to determine what kind of testing is needed exactly and how facilities might be designed to deliver the required data.

It was difficult for responders to seriously consider new subsonic or transonic WTs, given past failed attempts such as the facilities recommended by the *National Facilities Study* (1994),[8] current closures, greatly reduced RDT&E budgets, etc. No serious advocacy was identified for larger and flight-Rn WTs needed to realistically address "new" concepts such as active flow control and morphing in light of lessons learned with similar concepts.

Figure 2.5 shows that NASA's test facilities have more than $127 million in backlog of maintenance and repair (BMAR)—approximately equal to one year's worth of operating expenses. This large number in total is somewhat disturbing, although we did not specifically analyze what the effects of this large BMAR are on NASA's test facility operations.

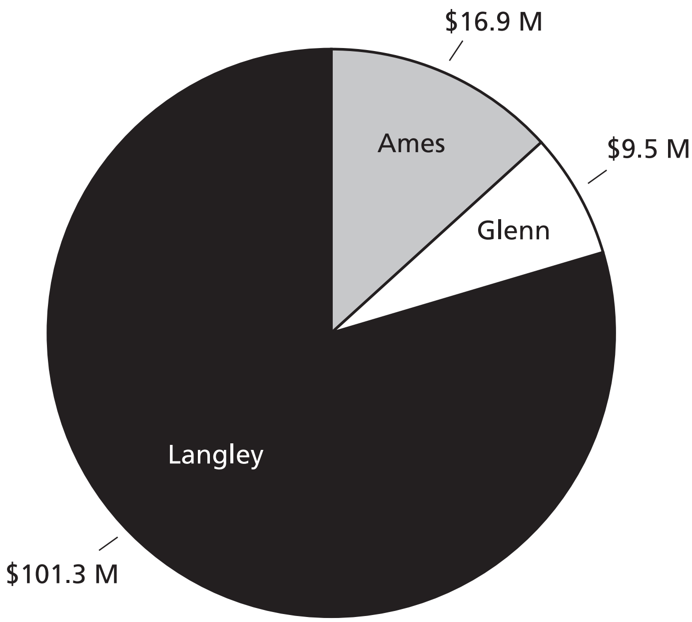
NASA WT/PT Facilities Are Generally Consistent with U.S. Needs, but Some Investments Are Needed

NASA's existing test facilities are generally consistent with the agency's research programs as well as the broader national needs. Tables 2.13 and 2.14 matched the National Aeronautic

[8] The *National Facilities Study* recommended the construction of two high-Rn, high-productivity, state-of-the-art facilities —one subsonic and one transonic. Despite repeated advocacy and discussion, the consortium of support never endured to generate the needed construction funds.

Test Alliance's (NATA's) WTs against the types of facilities the nation needs. Table 2.15 summarizes the status of NASA's existing WTs, including health ratings and issues (current usage levels, technical competitiveness with respect to state-of-the-art needs, and the lack of shared financial support to augment income from tests).

Figure 2.5
BMAR Across All NASA WT/PT Facilities



SOURCES: Personal communications and data: Ames, March 25, 2003; Glenn, March 25, 2003; Langley, March 27, 2003.
RAND *TR134-2.5*

Table 2.13
Roles of the 16 Existing NASA Subsonic to Supersonic WTs Under Study

Facility Type	Existing NASA Facilities
Eight Subsonic WTs	
General-Purpose	
Large, high Rn	Ames 12-Foot High-Rn Pressure
Large, atmospheric	Langley 14×22-Foot Atmospheric, Langley 12-Foot Atmospheric Lab
Special-Purpose	
Propulsion simulation	Glenn 9×15-Foot Propulsion Ames 80×120-Foot and 40×80-Foot Atmospheric National Full-Scale Aerodynamics Complex[a]
Very large, atmospheric	Ames 80×120-Foot and 40×80-Foot Atmospheric National Full-Scale Aerodynamics Complex
Icing	Glenn Icing Research Tunnel
Far-field acoustics	Ames 80×120-Foot and 40×80-Foot Atmospheric National Full-Scale Aerodynamics Complex[a]
Near-field acoustics	Glenn 9×15-Foot Atmospheric Propulsion[a] Langley 14×22-Foot Atmospheric[a]
Spin	Langley 20-Foot Vertical Spin Tunnel
Low turbulence	Langley Low-Turbulence Pressure Tunnel
Dynamics	Langley 14×22-Foot Atmospheric[a]

Table 2.13—Continued

Facility Type	Existing NASA Facilities
Five Transonic WTs	
General-Purpose	
Large, high Rn	Ames 11-Foot High-Rn
Medium, high Rn	Langley National Transonic Facility Very-High-Rn[a]
Large, atmospheric	Langley 16-Foot Atmospheric, Ames 11-Foot High-Rn[a]
Medium, atmospheric	Langley National Transonic Facility Very-High-Rn[a]
Special-Purpose	
Very-high Rn	Langley National Transonic Facility Very-High-Rn[a]
Propulsion simulation	Glenn 8×6-Foot Propulsion Langley 16-Foot Atmospheric[a]
Dynamics/flutter	Langley High-Rn Transonic Dynamics Tunnel
Three Supersonic WTs	
General-Purpose	
Large, high Rn	(Gap within NASA)
Medium, high Rn	Ames 9×7-Foot High-Rn
Small, high Rn	Langley 4-Foot High-Rn
Special-Purpose	
Propulsion simulation	Glenn 10×10-Foot Propulsion

[a]Secondary role.

Table 2.14
Roles of the 15 Existing NASA Hypersonic WT/PT Facilities and Direct-Connect PT Facilities Under Study

Facility Type	Existing NASA Facilities
Three Hypersonic WTs	
General-Purpose	
Low Mach	Langley 20-Inch Mach 6 Air
Moderate Mach	Langley 31-Inch Mach 10 Air
High Mach	n/a
Special-Purpose	
Real gas effects	Langley 20-Inch Mach 6 Tetraflouromethane
Nine Hypersonic Propulsion Integration	
Ramjet/scramjet suite	Langley 8-Foot High-Temperature Tunnel Langley Arc-Heated Scramjet Langley Combustion Scramjet Langley Supersonic Combustion Langley 15-Inch Mach 6 High-Temperature Tunnel NASA/GASL HYPULSE
Integrated engine tests	Ames 16-Inch Shock[b]
Longer-duration testing	Ames Direct-Connect[b] Glenn Propulsion Simulation Lab Cell 4[a]
Non-vitiated	Glenn Non-Vitiated Hypersonic Tunnel Facility
High Mach	n/a
Three Direct-Connect Propulsion	
Large engine and component	(Gap within NASA)
Medium engine and component	Glenn Propulsion Simulation Lab Cell 3, Glenn Propulsion Simulation Lab Cell 4
Small engine and component	Glenn Engine Components Research Lab Cell 2b

[a]Secondary role.
[b]Mothballed.

Table 2.15
Summary of Health Ratings of Existing WT/PT Facilities

Facility	Health Rating	Issues: Use	Issues: Tech	Issues: Shared Support
Subsonic WTs				
General-Purpose				
Ames 12-Foot PWT	Critical	X	X	X
Langley 14×22-Foot	OK			
Langley 12-Foot Lab	Critical	X	X	
Special-Purpose				
Ames NFAC (large size, rotorcraft)	Poor	X		X
Glenn IRT (icing)	Good			
Glenn 9×15-Foot (propulsion)	Fair			
Langley Spin Tunnel (spin)	Poor	?		
Langley LTPT (research)	OK			
Transonic WTs				
General-Purpose				
Ames 11-Foot UPWT	Poor			X
AEDC 16T	Good			
Special-Purpose				
Langley NTF (very-high Rn)	OK			
Langley TDT (dynamics/flutter)	Fair	X		
Glenn 8×6-Foot (propulsion)	Fair			
Langley 16 TT (propulsion)	Poor		X	
AEDC 4-Foot (store separation)	Good			
Supersonic WTs				
General-Purpose				
Ames 9×7-Foot UPWT	Poor	X		X
AEDC 16S	OK	X		
Special-Purpose				
Glenn 10×10-Foot (propulsion)	Poor	X		
Langley 4-Foot UPWT (smaller vehicles)	OK			
AEDC VKF A (continuity to hypersonic speeds)	Fair			
Hypersonic WTs				
General-Purpose				
Langley 20-Inch M6 CF4 Langley 20-Inch M6 Air Langley 31-Inch M10 Air	Good			
AEDC VKF A, B, and C; Tunnel #9	Good			
Special-Purpose				
ASC Channel 9 (research; dynamics)	OK			
Veridian 48- and 96-Inch Shock Tubes	Good			
CUBRC LENS I and II	Good			
Hypersonic Propulsion Integration				
Special-Purpose				
Langley 8-Foot HTT Arc Scramjet Combustion Scramjet SS Combustion 15-Inch M6 HTT NASA/GASL HYPULSE	OK			

Table 2.15—Continued

Facility	Health Rating	Issues		
		Use	Tech	Shared Support
Ames Direct-Connect	OK[a]	X	X?	X
Ames 16-Inch Shock	OK[a]	X	X?	X
Glenn PLS4[b]	Poor			
Glenn HTF	Fair	X		
AEDC APTU; Arc-Heated H3	OK			
ASC Channel 9	Good			
Veridian 48- and 96-Inch Shock Tubes	Good			
CUBRC LENS I and II	Good			
Direct-Connect Propulsion				
General-Purpose				
Glenn PSL-3 and PSL-4	Fair			
AEDC C, J, and T Cells	Good			
Special-Purpose				
Glenn ECRL 2b (small turbines)	Good			

[a]Mothballed before study commenced. Health ratings were based on experience with the facilities before closure. The facilities will likely need some investments before use.
[b]Rating for hypersonic propulsion integration purposes only; PSL-4 is rated higher under direct-connect propulsion testing.

CHAPTER THREE

Subsonic Wind Tunnels

Here we describe our analysis of the subsonic wind tunnels in light of our analysis of testing needs. The subsonic WTs studied are those with a Mach range of 0.0–0.6 and test cross-sections of 6 feet or more (in at least one dimension).

Tables 3.1 and 3.2 present an overview of the special capabilities and shortcomings (respectively) of the key NASA, DoD, for-hire, industry, Canadian, and European subsonic WTs. These tables present a summary of the findings from our analyses of the tunnel specifications and the responses we received from our questionnaires to the user community. The summary conveys the general pros and cons for these facilities and the complex nature involved in selecting a facility for a certain testing need rather than a comprehensive identification of all the technical factors and details for each facility. Additional technical specifications of these facilities, and the facility Web sites, can be found in Appendixes F and G.

The special capabilities identified in Table 3.1 include high or moderate Rn, flutter, spin, propulsion simulation, aeroacoustics, rotorcraft, STOVL, and icing. The only true high-Rn facilities are the NTF and the European Transonic Windtunnel (ETW) operating at all subsonic speeds and the National Full-Scale Aerodynamics Complex (NFAC) for full-scale vehicle tests up to 300 knots.[1] The Ames 12-Foot Pressure Wind Tunnel (PWT) is the highest Rn general-purpose subsonic capability in the United States at present. The Langley Low-Turbulence Pressure Tunnel (LTPT) also provides moderate-Rn capability with high-quality flows.

Table 3.2 shows the shortcomings identified for the tunnels listed in Table 3.1. Perhaps the most striking shortcoming across the tunnels is the large number of low-Rn facilities. Another notable observation is the large number of technical issues associated with the high-Rn Ames 12-Foot PWT. Compared with the capabilities of the foreign QinetiQ 5M, these shortcomings are striking and have driven the remaining commercial transport manufacturer (Boeing) to use the 5M in the United Kingdom. But some shortcomings are in the eye of the user. For example, many tunnels do not have external balances, but it was cited as a problem for Ames 12-Foot.

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[1] Rn for facilities is usually given as Rn per model foot. Thus, the final Rn for the test depends on how big a model can be tested in the tunnel. The maximum Rn for the NFAC is about 3 million per foot, but the very large size of the test section (up to 80 feet long) allows for very large models and thus high absolute Rn when the length of the test vehicle is taken into consideration. For example, smaller vehicles such as rotorcraft can be tested at full-size and flight-test conditions up to 300 knots in the NFAC.

Table 3.1
Special Capabilities of Existing Subsonic WTs

Owner	Subsonic-Capable WTs	Special Capabilities								
		Very-High Rn	High to Moderate Rn	Flutter	Spin	Propulsion Simulation	Aero-acoustics	Rotorcraft	STOVL	Icing
Ames	12-Foot PWT		√							
	NFAC (40×80-Foot, 80×120-Foot)		√			√	√	√	√	
Langley	14×22-Foot						√		√	
	LTPT		√							
	NTF at Low Mach	√	√							
	20-Foot Vertical Spin				√					
	12-Foot Atmospheric Lab									
Glenn	9×15-Foot Low Speed					√	√			
	10×10-Foot SS at Low Mach					√				
	IRT (icing)									√
AEDC	16T/S at Low Mach		√			√				
AFRL	10×7-Foot								√	
	12-Foot Vertical (BAR)				√					
Army	AAL 7×10-Foot at Ames							√		
Navy	NSWC 8×10-Foot Carderock									
Allied Aero	Micro Craft 8×12-Foot			√						
ODU	30×60-Foot		√							
Boeing	BVWT 20×20-Foot							√		
	BPWT 9×9-Foot					√				
	LSAF						√			
	BRAIT (icing)									√
LMC	16×23-Foot									
NGC	7×10-Foot			√						

Table 3.1—Continued

Owner	Subsonic-Capable WTs	Special Capabilities								
		Very-High Rn	High to Moderate Rn	Flutter	Spin	Propulsion Simulation	Aero-acoustics	Rotorcraft	STOVL	Icing
NRC/IAR	9M					√				
	5M Vertical				√					
QinetiQ	5M (Boeing/former DRA)		√			?	√			
BAE	5.5M×4.5M at Filton?					√				
	GER/AGF at Warton?								√	
DNW	LLF (20×20-Foot, 20×26-Foot)					√	√			
	KKK 2.4M (Cryo-atmos)		√							
	ETW at Low Mach	√	√							
ONERA	F1 at LaFauga (2.5×4.5M)		√							
	S1MA at Modane (8M)									

Table 3.2
Shortcomings of Existing Subsonic WTs

		Shortcomings									
Owner	Subsonic-Capable WTs	Poor User Advocacy	High Cost for R&D	Low Rn	Too Slow/ Small	No Force Testing	Poor Productivity	Cross-Section Shape	Poor STOVL	High Loads	No External Balance
Ames	12-Foot PWT	X	?					X		X	X
	NFAC (40×80-Foot, 80×120-Foot)										
Langley	14×22-Foot			X					X		
	LTPT				X						
	NTF at Low Mach		X[a]		X		X				
	20-Foot Vertical Spin										
	12-Foot Atmospheric Lab	X		X	X						
Glenn	9×15-Foot Low Speed			X		X					
	10×10-Foot SS at Low Mach			X		X					
	IRT (icing)			X							
AEDC	16T/S at Low Mach		X						X		
AFRL	10×7-Foot			X							
	12-Foot Vertical (BAR)			X							
Army	AAL 7×10-Foot at Ames			X							
Navy	NSWC 8×10-Foot Carderock			X							
Allied Aero	Micro Craft 8×12-Foot			X	X						
ODU	30×60-Foot										
Boeing	BVWT 20×20-Foot			X							
	BPWT 9×9-Foot			X							
	LSAF			X							
	BRAIT (icing)			X							
LMC	16×23-Foot			X							
NGC	7×10-Foot			X	X						

Table 3.2—Continued

Owner	Subsonic-Capable WTs	Shortcomings									
		Poor User Advocacy	High Cost for R&D	Low Rn	Too Slow/ Small	No Force Testing	Poor Productivity	Cross-Section Shape	Poor STOVL	High Loads	No External Balance
NRC/IAR	9M			X							
	5M Vertical			X							
QinetiQ	5M (Boeing/former DRA)		X								
BAE	5.5M×4.5M at Filton?										
	GER/AGF at Warton?										
DNW	LLF (20×20-Foot, 20×26-Foot)			X							
	KKK 2.4M (Cryo-atmos)										
	ETW at Low Mach				X		X				
ONERA	F1 at LaFauga (2.5×4.5M)		X								
	S1MA at Modane (8M)	X		X				X			

[a]Cryogenic.

Table 3.3 presents a summary of the advocacies received from current NASA programs, DoD representatives, and industry representatives for the eight existing subsonic tunnels at NASA. The advocacy data are illustrative and informative rather than comprehensive and dogmatic. We found internal inconsistencies in the responses—even within the same company—given that the responses were collected from multiple organizations with different needs within the same company. Also, verbal advocacy is somewhat suspect, since it is relatively inexpensive to give and does not require current payments or guarantees of future use. Of course, repeatedly unreliable advocacy can harm one's reputation in the long term, and we found the responses and discussions with the users to be thoughtful and balanced, appearing to reflect their strategic thinking beyond current test plans (which is exactly what we asked them to do).

The most strongly supported facilities were the Langley 14×22-Foot (as a default rather than for strong technical capabilities) and the Glenn Icing Research Tunnel (IRT).

Again, the shortcomings of the Ames 12-Foot PWT were evident, since Boeing, Lockheed Martin, and NAVAIR (Naval Air Systems Command) all had strong issues with various technical specifications of the tunnel. Also, one user raised issues with the Langley 14×22-Foot, citing an unsuitable STOVL capability and a currently dysfunctional moving ground plane.[2]

It was unclear why NAVAIR did not advocate for the Glenn IRT, given that icing is a significant issue for carrier operations.

Perhaps the most interesting observation from the advocacy data was the strong support for the NFAC across most users. As we will see below, this advocacy is not reflected in current utilization for the NFAC. We also know that history has shown that stated advocacy is not a reliable predictor of future utilization. For example, the NFAC upgrades in 1995–1998 and the complete rebuild of the Ames 12-Foot PWT have yet to produce an active user base for these facilities.

Health Ratings for Test Facilities

Table 3.4 lists the health ratings used to summarize the importance of issues facing each test facility based on our analysis of various facility factors, including apparent strategic importance, technical capabilities, utilization, user advocacy, uniqueness, strength of alternative facilities, financial health of the facility, etc. Lower numbers indicate weaker health.

Note that these ratings are *not* necessarily an indication of which facilities should be retained but rather are assessments of the overall health of the facilities. Some strategically important U.S. facilities have weak health ratings because of concerns about certain technical deficiencies, lack of financial support, or their current low utilization. NASA management should use these ratings to help identify which facilities need immediate attention.

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[2] Langley management indicated that the workforce that knew how to properly operate and maintain its 14×22-Foot moving ground plane has been lost, and low demand has prevented replacing this capability.

Table 3.3
Advocacies for Existing Subsonic WTs

	Ames		Langley				Glenn	
	12-Foot	NFAC	14×22-Foot	12-Foot	20-Foot Spin	LTPT	9×15-Foot	IRT
NASA								
Research and specific programs		√	√	√[c]		√	√	√
DoD								
Air Force ASC	√	√	√		√		√	√
Army (UAVs, missiles)			√					
Army rotorcraft		√	√					
NAVAIR	No	√	√	√	√		√	[d]
Industry								
Boeing								
–Commercial (transports)	No	√						√
–Tactical aircraft (manned; UCAV)	No	√	√					
–S. Calif. (ATT; high-speed vehicles)	√	√	√		√	√	√	√
–Hypersonic programs (space)	√	√	√					
–Rotorcraft[a]								
Bell Helicopter Textron		√						√
Gulfstream (business jets)[b]								
Lockheed Martin (tactical; UCAV)	No	√	No		√		√	√
Northrop Grumman (UAV; UCAV)	√							√
Raytheon A/C (GA; business jets)								√
Raytheon Missiles								
Sikorsky Helicopter		√	√					√

SOURCE: Responses to RAND's questionnaire, 2003.
[a]No response.
[b]Very generic response—no specific tunnels mentioned.
[c]Questionable data utility given very low Rn.
[d]Not mentioned but should need for aircraft carrier icing.

Table 3.4
Summary Health Ratings for Test Facilities

#	Health Rating	Criteria
5	Good	**Strong facility** • Strategically important; strong user base; financially healthy; most flexible overall capability available
4	OK	**Some issues** • Strategically important • Unique capability • Some technical or utilization issues • Possible investment candidate
3	Fair	**Moderate issues** • Somewhat unique capability, but important limitations • Moderate issues: utilization, technical, *or* workforce, etc.
2	Poor	**Significant issues** • Significant issues that need to be addressed: technical problems, market weaknesses, low utilization, unclear NASA/DoD/Industry role, *or* lack of center support endangering facility • Some strategic reasons to keep, but decisions and clarifications are needed
1	Critical	**Serious issues** • Serious (possibly fatal) issues: Hard to justify strategically, technically flawed, market weakness, very low utilization, *or* no institutional support for unused capacity endangering facility • If strategically important, then immediate attention is needed

Facilities rated a 5 are *strong*, strategically important facilities. They generally have a strong user base, are financially healthy, and have the most flexible overall capability available.

Facilities rated a 4 are *OK* but have some relatively *minor issues*. They are strategically important (often unique) facilities, although they have some technical or utilization issues. They may be possible candidates for some level of investment for improvement.

Facilities rated a 3 have *moderate weaknesses*. They may offer a somewhat unique capability but have important limitations. Moderate issues can include utilization, technical, or workforce concerns.

Facilities rated a 2 have *significant issues* for which management should take action soon. These issues may include technical problems, market weaknesses, low utilization, unclear NASA/DoD/industry role, or lack of shared support that could or is endangering the facility. There may be some strategic reasons to keep the facility, but management needs to make some clear decisions, clarifications, and actions regarding its future.

Finally, facilities rated a 1 have *serious deficiencies* for which management should take immediate action. These (possibly fatal) issues may include difficulty in justifying the facility strategically, technical flaws, market weaknesses, very low utilization, or no shared support for unused capacity that is endangering the facility.

Subsonic WT Health Ratings and Summary Descriptions

Table 3.5 summarizes our analysis of NASA's subsonic WTs—both those that are general purpose and those with special-purpose technical capabilities. We gave each tunnel an overall health rating using the levels from Table 3.4.

Table 3.5
Health Ratings and Summaries of Existing Subsonic WTs

Name	Health	Summary
General-Purpose Facilities		
Ames 12-Foot PWT	Critical	• Only high-Rn facility in the United States, but has undesirable features • Poor user support; viewed as unacceptable by important industry segments • QinetiQ (Boeing?) 5 Meter is much preferred choice
Langley 14x22-Foot	OK	• Good advocacy • Only one suitable (?), albeit low Rn and some detractors • Must identify viable NASA and other research needs
Langley 12-Foot Lab	Critical	• Very low Rn, but cheap and available • Very questionable applicability of any data
Special-Purpose Facilities		
Ames NFAC (large size, rotorcraft)	Poor	• Vocal advocacy for enabling capabilities for rotorcraft from the DoD and industry • Sparse utilization (nothing like projections) • Occasional other utilization (airframe noise, inlet instrumentation, base flows)
Glenn IRT (icing)	Good	• Strong support—all segments • NASA research staff very capable and helpful
Glenn 9x15-Foot (propulsion)	Fair	• Supporting noise reduction research; some DoD advocacy • Low Rn and no force testing capability • Could AEDC 16T or 16S, operating at low Mach, satisfy this requirement?
Langley Spin Tunnel (spin)	Poor	• Best capability available, but DoD only • Sparse usage?
Langley LTPT (research)	OK	• Unique high-Rn research capabilities • Need to identify viable NASA and other research objectives requiring this facility

General-Purpose High-Rn Subsonic WTs

Ames 12-Foot Pressure Wind Tunnel

The Ames 12-Foot PWT is the only general-purpose high-Rn subsonic WT in the United States (since the NFAC is not generally suitable for most vehicle types requiring high Rn).

However, the Ames 12-Foot has very limited support and advocacy from industry. The QinetiQ 5M in the United Kingdom (retained by Boeing) is either the primary or only choice for users because of its superior features and technical capabilities. The deficiencies of the 12-Foot were reflected by a number of notable strong critics—for example, some unresolved deficiencies (highlighted by NAVAIR) not addressed by Ames center management because of its lack of support for WTs. France's ONERA (Aeronautics and Space Research Center) F1 is also a possibility for some applications.

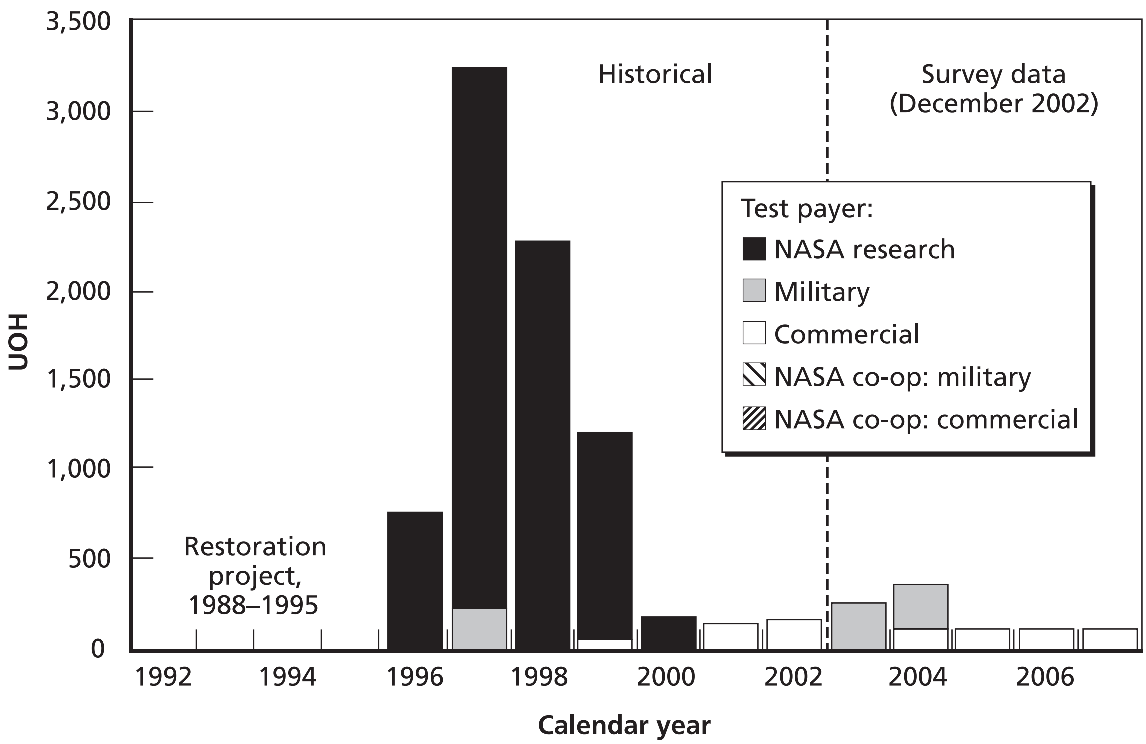
As a result of Ames's lack of shared support for local WTs, the Ames 12-Foot is not affordable for most research needs, despite its capabilities and usefulness in prior programs such as the Space Shuttle. This situation is aggravated by the lack of local R&D programs and thus staff at Ames, reducing the 12-Foot's attractiveness for research use.

As a result of the superior (albeit foreign) alternatives in a prevailing acquisition approach encouraging contractors to select facilities based on cost and availability (regardless of country), the Ames 12-Foot has had very low utilization since its rebuild from 1988 to 1995 (see Figure 3.1). The extended unavailability of the 12-Foot did not help. Users were forced to seek out alternatives, and they established databases and experience with the 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.

Anecdotal evidence and experiences showed that, while some in industry pressed NASA to rebuild the 12-Foot to the same technical specifications (to preserve their investments in test databases), other industry users advocated for expanding the capabilities of the tunnel to address issues such as the size and shape of the test section. Pragmatic forces prevailed, since a rebuild is easier to defend than constructing a new tunnel. Unfortunately, the current situation indicates that this decision turned out to be shortsighted. The rebuild decision would have been a good time to consider consolidating facilities in fewer centers to begin consolidating the fixed shared supporting infrastructures. The lesson learned here is not to affix blame but to try to avoid missing similar opportunities to both advance U.S. design capabilities and consolidate facilities.

Figure 3.1 shows the historical utilization of the Ames 12-Foot PWT. Facility upgrades are shown as construction of facilities (CoF) in the year they occurred, since they often affect facility availability. Utilization is given in user occupancy hours (UOH) and has been broken down in each fiscal year by which sector paid for the test: NASA (directly for a NASA research program), a military program (directly for either a DoD organization or a

Figure 3.1
Historical Utilization and Identifiable Future Testing Hours at Ames 12-Foot Pressure Wind Tunnel by Test Payer



SOURCES: NASA Ames and December 2002 RAND survey data.
RAND *TR134-3.1*

military contractor), commercial industry for commercial research or vehicle production, or a cooperative program with either a DoD (military) or commercial industry partner for which NASA paid for the test costs. The small amount of projected testing indicated in our survey data from December 2002 is military utilization for the JSF program (as backups to the 5M); commercial forecasts were for the Boeing Advanced Theater Transport (ATT).

The Ames 12-Foot, therefore, has a poor strategic position in addition to poor utilization. It is the only high-Rn facility in United States, but has undesirable features given *foreign* alternatives. The QinetiQ 5M is the much preferred choice in a globalized commercial business environment. The Ames 12-Foot has poor user support and is viewed as unacceptable by important industry segments. It is hard to justify investing $100 million or more to address the tunnel's deficiencies absent guaranteed work from NASA research or from the transport manufacturing community. It is also difficult to view the 12-Foot as an effective domestic backup to the 5M, since lack of use will not develop and retain a skilled workforce. NASA recently announced the one-year mothballing of the 12-Foot at the end of FY2003 because of its very low utilization and lack of shared support from Ames. It may be prudent, however, to mothball the new facility in the long term as a backup to the 5M and F1 rather than abandon it completely. This would preserve the country's sole high-Rn facility in case a need to use it arises in the next five to ten years. The workforce issue in this case is not as severe because there is 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 (see discussion below), then a more permanent decision can be made concerning the 12-Foot.

General-Purpose Atmospheric Subsonic WTs

Langley 14×22-Foot Subsonic Wind Tunnel

The Langley 14×22-Foot Subsonic Wind Tunnel is a low-Rn, atmospheric, moderate-size facility with strong advocacy from the rotorcraft, UCAV, and high-speed vehicle communities. It has a moving ground plane for ground effects and is the only NASA multipurpose subsonic WT currently affordable for NASA research.

However, the Langley 14×22-Foot is becoming well used as a default facility, despite its technical shortcomings. But it has one strong critic of the quality of the facilities ground plane and STOVL simulation capabilities. Its low Rn is for preliminary research, but there is no affordable high-Rn facility available for subsequent research and technology transition work needed for some vehicle types. The Boeing V/STOL Wind Tunnel (BVWT) and Lockheed Martin 16×23-Foot are suitable, productive U.S. alternatives to the 14×22-Foot. The DNW Large Low-Speed Facility (LLF) is better suited for STOVL investigations, according to the JSF program.

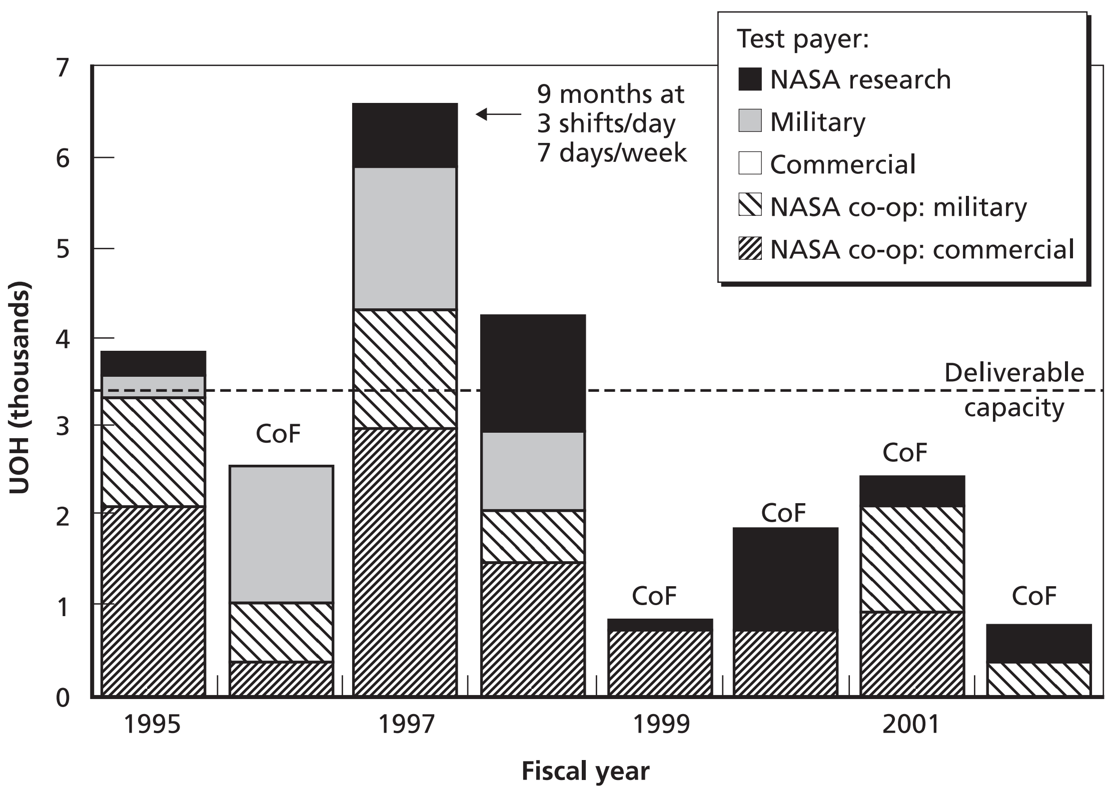
Figure 3.2 shows strong historical utilization at the 14×22-Foot, even during CoF upgrades. The large surge in utilization beyond the nominal capacity of the facility was achieved by operating three shifts a day for seven days a week for nine months.

The biggest concern with the 14×22-Foot is the resolution of NASA's role in retaining a multipurpose subsonic WT when the agency's own aeronautic program is in decline and when low-Rn testing only satisfies some preliminary research needs. NASA's shift away from maintaining facilities for DoD research topics and other potential user needs raises some questions, especially when industry is closing their private facilities (e.g., Boeing's St. Louis facilities and the UTRC).

Langley 12-Foot Wind Tunnel Laboratory

The Langley 12-Foot subsonic facility is characterized as a very inexpensive atmospheric WT laboratory. It has very-low-Rn capabilities but is inexpensive and available. The 14×22-Foot is a larger, inexpensive alternative (although Langley management indicated that testing costs in the Langley 12-Foot are about one-fifteenth that of the still-inexpensive 14×22-Foot). The Langley 12-Foot has poor user advocacy (see Table 3.3) and is viewed as unacceptable by important industry segments. Figure 3.3 shows that the Langley tunnel has a poor utilization history and poor forecasted future need. All told, the Langley 12-Foot has a poor strategic position, yet very low testing costs and the very small gains from closing the facility may dictate keeping it open.

Figure 3.2
Historical Utilization at Langley 14×22-Foot by Test Payer



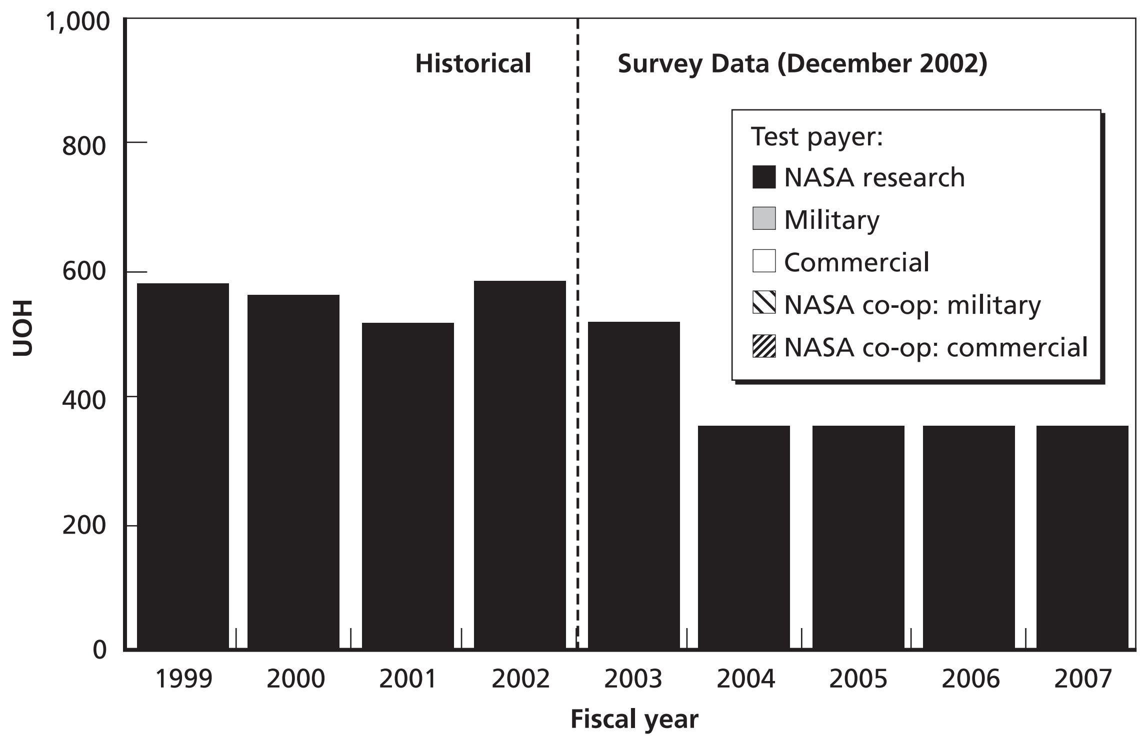
SOURCE: NASA Langley.
RAND *TR134-3.2*

Special-Purpose Subsonic WTs

Ames National Full-Scale Aerodynamics Complex

The Ames NFAC is a subsonic facility used primarily for rotorcraft RDT&E. The NFAC is unique in the world because of its extreme size and ability to hold full-scale rotorcrafts. The tunnel is not generally suitable for most vehicle types requiring high Rn. The NFAC has strong verbal advocacy from rotorcraft researchers and industry and is an enabling capability for any advanced rotorcraft concepts. Its large size can be exploited for other applications, such as some flow control applications (if they are ever pursued). Major advocacy is by DoD-type programs, although some NASA-applicable usage (e.g., airframe noise) is anticipated. The JSF program considered using the NFAC for inlet compatibility (i.e., density of instrumentation required), but when NASA mothballed the facility, the JSF program office decided not to rely on the facility and incurred the added risks from not performing these tests. The NFAC is also needed for some space access vehicle applications (i.e., base-flow acoustics on carrier aircraft). In many of these cases, there is no acceptable alternative anywhere in the world.

Figure 3.3
Historical Utilization and Identifiable Future Testing Hours at the Langley 12-Foot by Test Payer



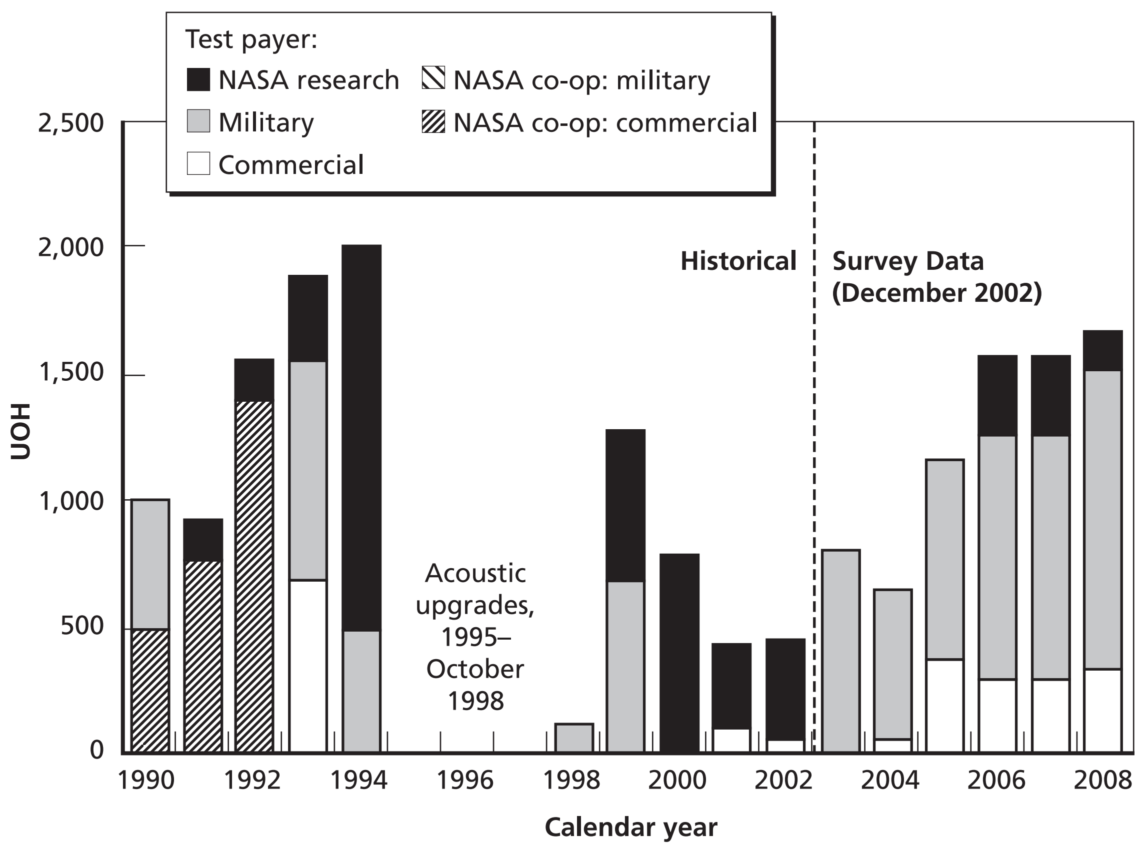
SOURCES: NASA Langley and December 2002 survey data.
RAND *TR134-3.3*

However, the NFAC is not really a general-purpose facility. To achieve flight Rn, models would have to be full-scale (or nearly so), essentially requiring the full-scale construction of the vehicle in advance of obtaining performance data on the aerodynamic designs under consideration and refinement. The NFAC's recent utilization has been very low to the point where, like the Ames 12-Foot PWT, NASA has recently announced the one-year mothballing of the facility at the end of the fiscal year 2003 because of its very low utilization and the lack of shared support from Ames.

Figures 3.4 and 3.5 show the historical utilization for the two NFAC test sections, respectively: the 40×80-Foot and 80×120-Foot test sections. The NFAC was shut down for facility acoustic modernization in 1995 and began operation again in October 1998.

The small amount of projected testing indicated in our survey data from December 2002 for the 40×80-Foot was for NASA research (Quiet Aircraft Technology program), military (Army rotorcraft program), and commercial aircraft (Boeing ATT and Bell quad-tilt rotorcraft). The projected testing for the 80×120-Foot was military (Army rotorcraft program).

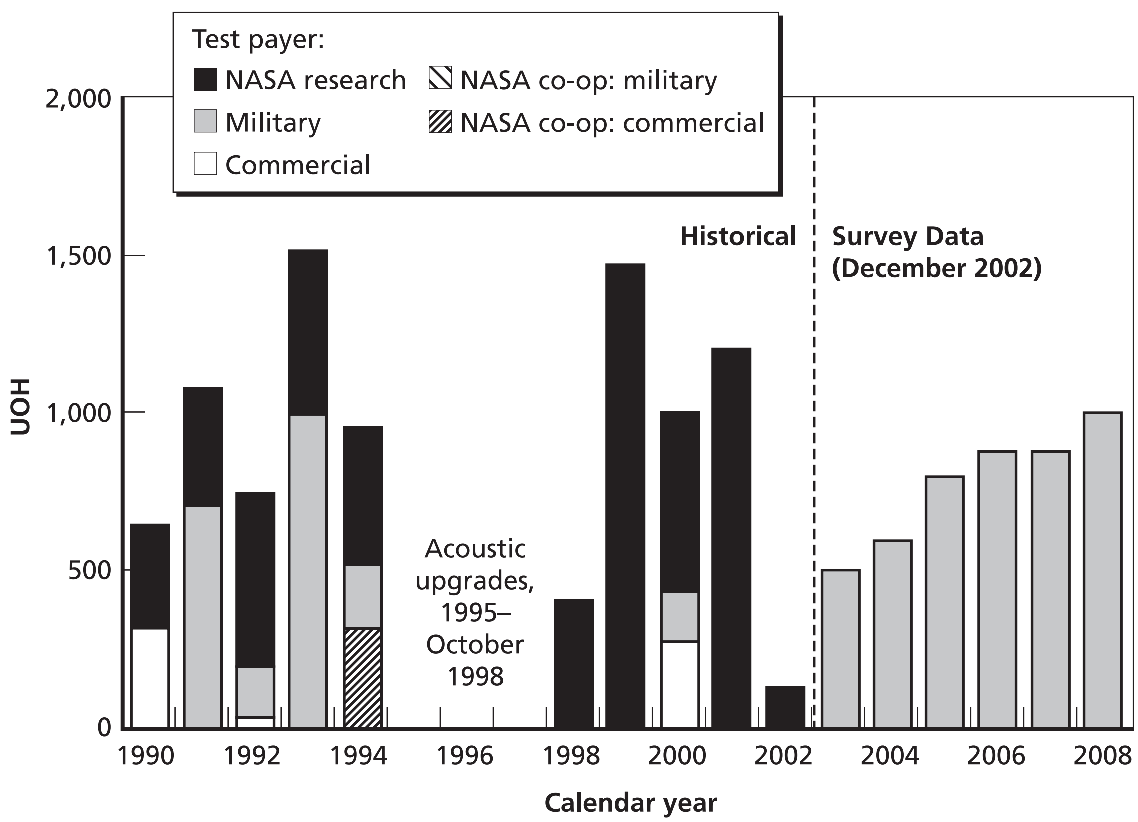
Figure 3.4
Historical Utilization and Identifiable Future Testing Hours at the Ames NFAC 40×80-Foot Test Section by Test Payer



SOURCES: NASA Ames and December 2002 survey data.
RAND *TR134-3.4*

The recent elimination of the NASA rotorcraft research program[3] has been the biggest blow to the health of the NFAC. The Army rotorcraft program did not have funds budgeted to immediately assume the full costs of keeping the facility open, and the DoD is scrambling to assess the strategic effect of NASA's decision. The inability of Ames and NASA headquarters to identify stopgap funding to keep the NFAC open endangers a strategic resource long used by NASA research, the DoD, and the commercial sector. This may be a shortsighted position based on near-term funding limitations that may not be in the best long-term interest of the nation if the NFAC is needed in the future. Severe budgetary constraints have been tying NASA's hands so that, as the agency cuts its R&D programs in aeronautics because of budgetary pressures, national resources are also endangered. The Office of Management and Budget, the White House, and Congress need to realize what is likely to happen as a result of decreased aeronautic R&D funding.

Figure 3.5
Historical Utilization and Identifiable Future Testing Hours at the Ames NFAC 80×120-Foot Test Section by Test Payer



SOURCES: NASA Ames and December 2002 survey data.
RAND *TR134-3.5*

[3] See the NASA Office of the Chief Financial Officer (n.d.).

Glenn Icing Research Tunnel

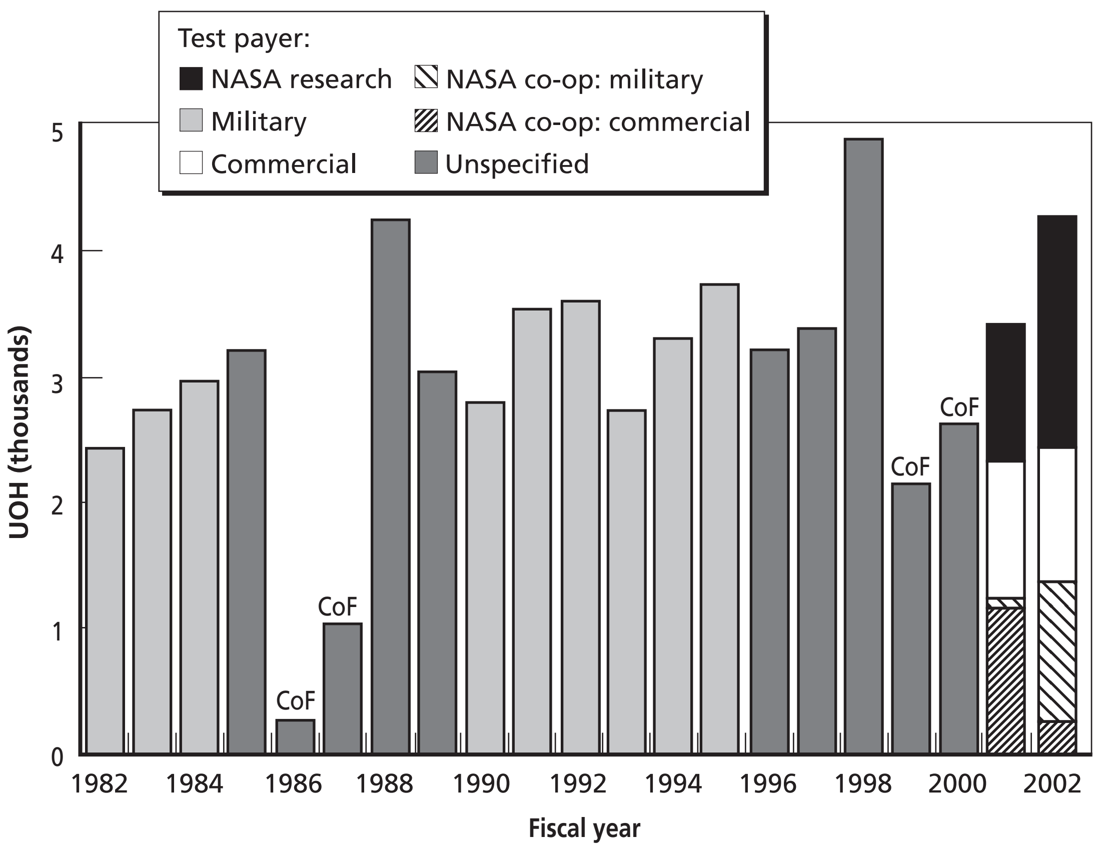
The IRT is a good example of a special-purpose primary facility. It has a strong strategic capability to meet continuing needs for icing RDT&E and has very strong advocacy from all user sectors. Its workforce is highly recognized and valued, and the facility has had consistently high utilization in recent history (see Figure 3.6).

Glenn 9×15-Foot Propulsion Wind Tunnel

The Glenn 9×15-Foot PWT is a special-purpose facility primarily used for NASA propulsion research, with some military backup potential. NASA has used the 9×15-Foot for engine exhaust noise reduction studies, and the facility has some advocacy from the DoD (ASC and NAVAIR). Glenn has local research staff with identified needs for the 9×15-Foot. Figure 3.7 shows that the combined historic utilization of the Glenn 9×15-Foot along with its linked transonic 8×6-Foot test section has been quite high.

However, the 9×15-Foot is a low-Rn facility. Its lack of a force testing capability prevents it from being a general-purpose WT. It has very little advocacy from either airframe or engine manufacturers. DoD advocacy (for inlet compatibility) was not supported by Lockheed Martin ("too small"). The AEDC 16S (at low speed) is a possible (albeit more expensive) alternative.

Figure 3.6
Historical Utilization at Glenn Icing Research Tunnel by Test Payer



SOURCE: NASA Glenn.
RAND *TR134-3.6*

The only issues with the 9×15-Foot surround the question of whether the AEDC 16T or 16S could be modified to meet the tunnel's capabilities in subsonic speed, noise-flow quality, and propulsion simulation. The high utilization and strong advocacy for the 9×15-Foot, however, indicates that it is relatively strong within NASA as long as the movement toward full-cost recovery does not endanger its shared support.

Langley 20-Foot Vertical Spin Tunnel

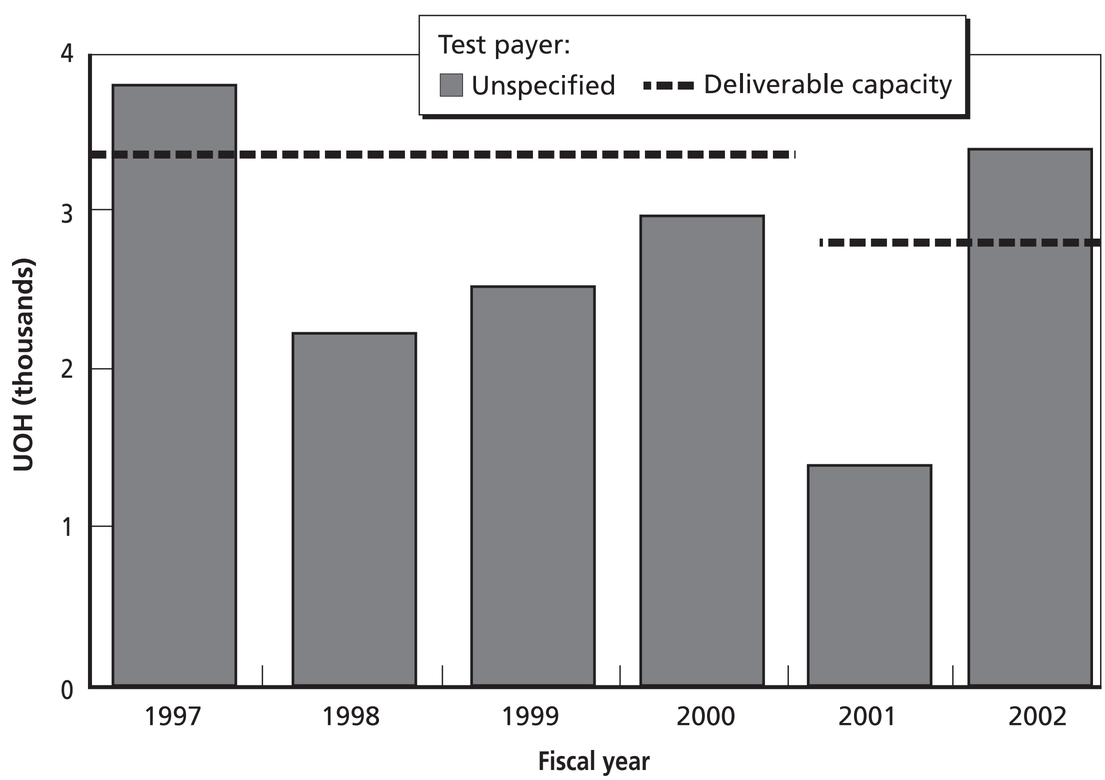
The Langley 20-Foot Vertical Spin Tunnel is the best capability available for atmospheric studies of spinning, tumbling, and free-fall characteristics of aircraft and spacecraft. Usage appears sparse and is dominated by the military.

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.

However, viable NASA and other research objectives that require this facility need to be clarified (recall, for example, the concerns raised above about LFC concepts).

Figure 3.7
Combined Historical Utilization at Glenn 9×15-Foot Subsonic and 8×6-Foot Transonic Propulsion Wind Tunnels



SOURCE: NASA Glenn.
RAND *TR134-3.7*

Conclusions and Recommendations for Existing Subsonic WTs

The United States does not have an adequate high-Rn general-purpose subsonic WT that meets all domestic user needs. The Ames 12-Foot PWT is the only U.S. capability in this category and has been historically important for civil, space, and military vehicle RDT&E. Currently, however, the facility has some undesirable features and limitations that render it unacceptable for both commercial transport and tactical aircraft development when compared with the two superior facilities in Europe: the QinetiQ 5M in the United Kingdom and the ONERA F1 in France. Technical differences were supplemented by the long downtime from 1988 to 1995 for the Ames 12-Foot reconstruction, forcing users to foreign facilities and establishing experience and databases at the 5M. Both the military and commercial U.S. industry segments find that the QinetiQ 5M facility very adequately fills their needs in this regime, and the 5M appears to be suitable for all other identified U.S. needs. Thus, the Ames 12-Foot PWT could be considered redundant *if* the costs associated with NASA testing in Europe are satisfactory and availability arrangements could be made satisfactory. Verbal indications are that QinetiQ is looking for additional reliable usage for its facility and would probably welcome discussions with NASA. More importantly, however, such a reliance arrangement *assumes that the United States wants to rely on a foreign facility for such a strategic test capability* important not only for the commercial sector but for military vehicles important to national security.

The inability of Ames and NASA headquarters to identify stopgap funding to keep the NFAC open endangers a strategic resource long used by NASA research, the DoD, and the commercial sector. This may be a shortsighted position based on near-term funding limitations that may not be in the best long-term interest of the nation if the NFAC is needed in the future as indicated by the strong advocacy from numerous user communities.

The fate of the Ames NFAC and Langley spin tunnels also appear to hinge on the clarification of roles and relationships between NASA and the DoD; both are currently, but not exclusively, used for military programs.

Before decisions are made regarding the future viability of the Glenn 9×15-Foot, Langley LTPT, and Langley 14×22-Foot), NASA (with inputs from the DoD) needs to carefully define viable aeronautic research topics for vehicle categories of interest to the production community for the agency's research efforts.

Despite uses by the NASA Aviation Safety Program, the Langley 12-Foot laboratory has a generally unacceptably low-Rn capability, rendering it technically unacceptable for most applications. It is redundant to the Langley 14×22-Foot facility for most applications (although Langley management indicated that the 12-Foot costs about one-fifteenth as much for a test as the 14×22-Foot). Thus, the Langley 12-Foot is also a technically unneeded and redundant capability (except for its low cost).

Finally, good lessons can be learned from the Glenn IRT example of maintaining expert NASA researchers closely involved with the tunnel's operations. Low utilization of the IRT in the 1960s and 1970s, in contrast with its very high utilization today, illustrates the long-term cyclic nature of facility utilization and the importance of looking long-term in strategic decisions concerning the retention of unique facilities important to aeronautics RDT&E.

CHAPTER FOUR

Transonic Wind Tunnels

Here we describe our analysis of the transonic wind tunnels in light of our analysis of testing needs. The transonic WTs studied are those with a Mach range of 0.6–1.5 and test cross-sections of 4 feet or more (in at least one dimension).

Table 4.1 presents an overview of the special capabilities and shortcomings of the key NASA, DoD, for-hire, industry, Canadian, and European subsonic WTs. As with the subsonic facilities, these tables present a summary of the findings from our analyses of the tunnel specifications and the responses we received from our questionnaires sent to the user community. This summary conveys the general pros and cons for these facilities and the complex nature involved in selecting a facility for a certain testing need rather than a comprehensive identification of all the technical factors and details for each facility. Additional technical specifications of the facilities, and the facilities' Web sites, can be found in Appendixes F and G.

The special capabilities identified in Table 4.1 include high or moderate Rn, propulsion simulation, store separation simulations,[1] flutter, and good speed ranges. Unlike for subsonic tunnels, the U.S. government has excellent high-Rn transonic facilities with the NTF, AEDC 16T, and Ames 11-Foot. The ETW in Germany is a next-generation high-Rn R&D facility built upon the lessons learned in the United States in the NTF; it shares in the productivity and speed range limitations of the NTF as well. Propulsion simulation capabilities can be found at the AEDC 16T and Glenn 8×6-Foot, and the AEDC 16T and 4-Foot tunnels offer store separation capabilities.

Table 4.2 presents a summary of the advocacies received from current NASA programs, DoD representatives, and industry representatives for the five existing transonic WTs at NASA. The two transonic facilities at AEDC provide important user context, so we included their advocacies as well for perspective. The advocacy data are illustrative and informative rather than comprehensive and dogmatic. As with the advocacies shown before, we note that such strategic advocacies are enlightening but do not necessarily predict future utilizations.

A recurring theme in the questionnaire responses was that high-Rn facilities are often unaffordable within today's extremely tight budgets (especially for R&D budgets at NASA), despite solid technical needs for these programs to be testing in high-Rn facilities. This disconnect is worrisome and reflects an inability of test engineers to prevail in today's climate of

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[1] Store separations involve the simulated effects when two bodies separate from each other within the airflow. Examples include weapons separating from a fighter or bomber, or the separation of external fuel tanks from a space vehicle.

Table 4.1
Capabilities and Shortcomings for Existing Transonic WTs

			Special Capabilities							Shortcomings						
Owner	Tunnels	Max. Mach #	Very-High Rn	High Rn	Propulsion Simulation	Store Separation	Good Mach Range	Flutter	Blow-Down	Low Rn	Min. Force Test	Poor Produc-tivity	Inadequate Max. Mach	Too Small for Some	Model Dynamics at Cryo. Temp	Poor Flow Quality
Ames	11-Foot Transonic	1.5		√			√									
Langley	16-Foot Transonic	1.3			√					X			X			
	NTF	1.2	√	√								X	X		X	
	TDT	1.2		√				√					X			
Glenn	8×6-Foot Transonic	2.0			√		√			X	X					
AEDC	16-Foot PWT	1.6		√	√	√	√	√								
	4-Foot PWT	2.0			√	√								X		
Veridian	(Calspan) 8-Foot	1.4			√	√		√		X			X			
Allied Aerospace	7-Foot Trisonic Blowdown	3.5		√			√		√							
Boeing	BTWT 8×12-Foot	1.1			√					X			X			
	PSWT 4-Foot	5.0					√		√					X		
Lockheed Martin	4-Foot	4.8			?				√					X		
NRC/IAR	1.5M Trisonic Blowdown	4.3		√			√		√					X		
ARA	9×8-Foot TWT	1.4			√								X			
BAE	4-Foot at Wharton	?			?									X		
DNW	ETW at Cologne	1.4	√	√								X	X		X	
	2×1.8M HST at NLR	1.4		√									X			
ONERA	S2MA 1.75×1.77M	3.1			?											
FOI	HSWTT1500 (1.5M)	1.3											X	X		

Table 4.2
Advocacies for Existing Transonic WTs

	Ames	Langley			Glenn	AEDC	
	11-Foot	**NTF**	**16TT**	**TDT**	**8×6-Foot**	**16T**	**4T**
NASA							
Research and specific programs		√	√[a]	√	√		
DoD							
Air Force ASC	√		√	√	√	√	√
Army (UAV and missiles)			√				
Army Rotorcraft				√			
NAVAIR	√		√		√	√	√
Industry							
Boeing							
–Commercial (transports)	√	√		√		√	
–Tactical A/C (manned; UCAV)	√			√		√	√
–S. Calif. (ATT; high-speed vehicles)	√	√	√	√		√	√
–Hypersonic programs (space)	√		√			√	
–Rotorcraft[c]							
Bell Helicopter Textron				√			
Gulfstream (business jets)[b]							
Lockheed Martin (tactical; UCAV)				√	√	√	√
Northrop Grumman (UAV; UCAV)	√			√		√	
Raytheon A/C (GA; business jets)[c]							
Raytheon Missiles							
Sikorsky Helicopter	√						

[a]Some programs identified (Next-Generation Launch Technology), but 16TT slated for closure. Viable given low Rn?
[b]Very generic response—no specific tunnels mentioned.
[c]No response.

continued reductions in aeronautic RDT&E budgets at NASA and in commercial firms. Lessons learned from past programs as detailed in Chapter Two suggest that program failures and design surprises may occur in production programs as a result of reduced testing at high (near-flight) Rn. The pace of advancement in NASA R&D will also be adversely affected by lack of access to the nation's premier high-Rn facilities.

Transonic WT Health Ratings and Summary Descriptions

Table 4.3 summarizes our analysis of NASA's (and selected DoD) transonic WTs—both general-purpose tunnels and those with special-purpose technical capabilities. Each tunnel was given an overall health rating using the levels from Table 3.4 in Chapter Three.

General-Purpose, High-Rn Transonic WTs

Ames 11-Foot Transonic Unitary Plan Wind Tunnel

The Ames 11-Foot Unitary Plan Wind Tunnel (UPWT) is one of only two large, high-Rn (but not necessarily flight-Rn for larger vehicles) transonic WTs in the world now available.

Table 4.3
Health Ratings and Summaries of Existing Transonic WTs

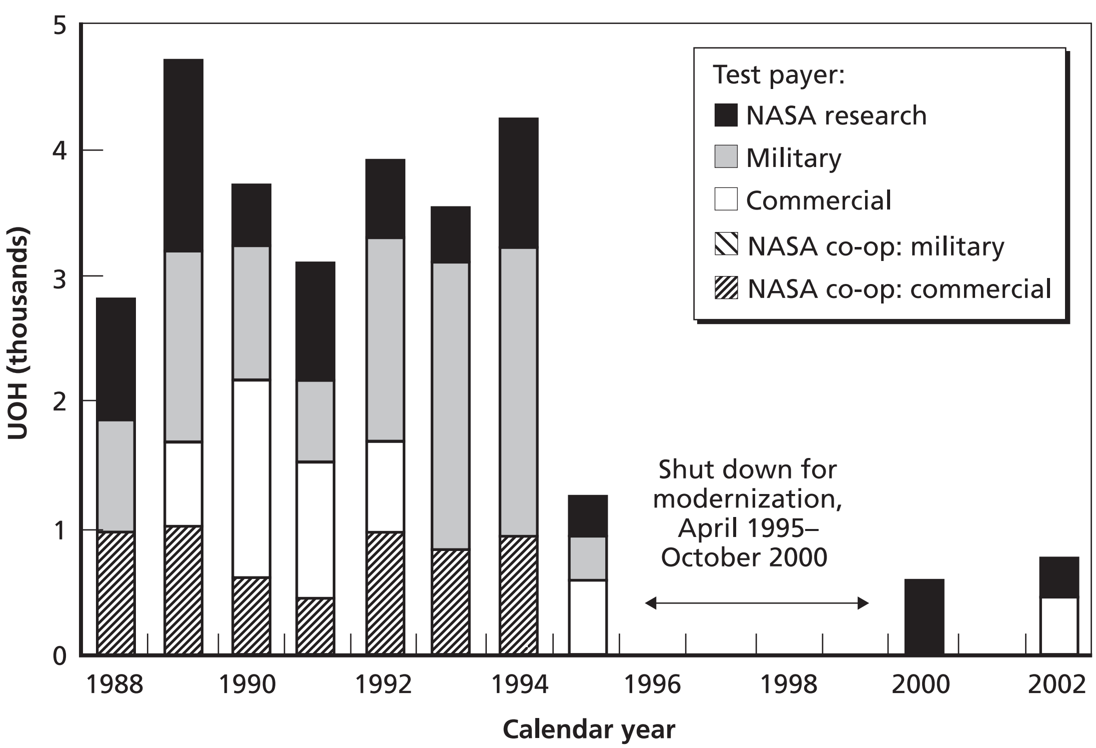
	Health	Summary
General-Purpose Facilities		
Ames 11-Foot UPWT	Poor	• Good track record, high-Rn, good Mach range, but poor recent utilization • No propulsion simulation, too expensive for many users (CA power concerns) • AEDC 16T acceptable alternative for all advocates if available and affordable
AEDC I6T	Good	• Overall best (high-Rn; Mach range, propulsion capability, size, store separation; Rn; compatible with 16S) • *Cost* and *availability* are the main concerns. New pricing? • Large size is overkill for some applications (missiles, etc.)
Special-Purpose Facilities		
Langley NTF (very-high Rn)	OK	• Excellent very-high-Rn research capability • Low productivity and model dynamics limitations (at cryogenic temperatures) • More productive air-only capability would broaden support
Langley TDT (dynamics/flutter)	Fair	• Unique for transonic dynamics • Primary advocacy is from DoD programs, with some NASA research uses • Limited Mach range, questionable interpretation of data with $\gamma \neq 1.4$
Glenn 8×6-Foot (propulsion)	Fair	• Excellent Mach range. Has propulsion simulation capability • Low Rn, no force measurements, and not an effective backup to AEDC 16T • Need to define viable research objectives requiring this facility
Langley 16TT (propulsion)	Poor	• Long history of enabling effective NASA contributions to DoD tactical aircraft • Potential backup to AEDC 16T, but has inadequate Mach range, low Rn, and poor flow quality • Sought after because of affordability and availability, esp. for NASA and DoD research
AEDC 4-Foot (store separation)	Good	• Unique store separation testing capability; has propulsion simulation • Appropriate for smaller vehicle and missile investigations

It is readily available, has good transonic Mach number capability (i.e., up to 1.5), and is compatible with the Ames 9×7-Foot supersonic facility (albeit the 9×7-Foot has limited Mach number range). There is substantial user familiarity with the facility (databases, calibration, etc.). The 11-Foot is typically relied on for production configuration validation and data gathering at present, given the lack of aerodynamic research programs at Ames.

However, the Ames 11-Foot is often considered too expensive in the current business environment where cost is the driving metric, especially for any research or preliminary-design-type testing. The facility ranks second to AEDC 16T in technical capabilities, since the 11-Foot has no propulsion simulation capability and the 16T together with 16S at AEDC is a better combination. Finally, the facility has very low recent utilization, since it was closed for major overhaul in from 1996 to 1999 (see Figure 4.1). The DoD and industry have historically been major users of the tunnel, but those users have yet to return. Combined with the lack of local research and shared support from Ames, the lack of paying users is endangering this quality facility.

As one of the world's two premier transonic facilities, one might ask whether the Ames 11-Foot can be considered a viable backup or alternative to AEDC 16T. Is it needed or desirable? Is limited access to AEDC 16T a viable concern (requiring an expensive insurance policy of keeping the 11-Foot open)? Are concerns voiced regarding AEDC 16T costs (relative to the Ames 11-Foot) valid?

Figure 4.1
Historical Utilization at the Ames 11-Foot UPTW by Test Payer



SOURCE: NASA Ames.
RAND *TR134-4.1*

The Ames 11-Foot is not an adequate backup to the AEDC 16T if propulsion simulation is required or if the smaller size could be a concern (for models sized for the 16T). There are also concerns regarding the viability of retaining a backup facility when utilization is so low. Maintaining an effective and knowledgeable operating staff during extended down periods is difficult without resources. Considering NASA by itself, the Ames 11-Foot is unique and may be important for future research programs requiring high Rn in a high-productivity environment (as opposed to the NTF, which lacks high productivity). Reliance, availability, and cost concerns (e.g., for the AEDC 16T) should be addressed before NASA ventures to remove the 11-Foot from its tool set.

Finally, the 11-Foot might be valuable enough to commercial companies for them to consider either taking it over and operating it, or entering into a retainer in the way Boeing is doing with the QinetiQ 5M subsonic tunnel.

AEDC 16T Propulsion Wind Tunnel

The DoD's AEDC 16-Foot PWT has the best overall technical capability of any transonic WT in the United States (except for the Langley NTF's very-high-Rn but lower-productivity R&D capability). The AEDC 16T has a high-Rn capability, the best overall propulsion simulation capabilities, good transonic Mach number speed range, more than adequate size, and excellent compatibility with AEDC 16S. The AEDC 16T is a clear choice as a national primary facility based on technical capability and maximum flexibility provided.

However, the large size, and thus higher direct testing costs, of the AEDC 16T is too expensive for many smaller vehicle types and missiles because users are charged direct testing costs by the Air Force. It is likely unaffordable for most research and preliminary design studies. Respondents expressed concern in our questionnaires regarding adequate and timely access and availability to the AEDC 16T, especially for low-priority, nonmilitary programs. Calibrations would have to be undertaken, and databases established, if this facility were taking the place of the Ames 11-Foot.

At issue is whether there will be adequate access and availability for NASA and non-DoD industry for research, development, and production testing if the Ames 11-Foot becomes unavailable (i.e., is closed) and the Langley 16TT is closed as planned (Skora, 2002a).

Some respondents expressed a concern that testing costs in the AEDC 16T relative to the NASA Ames-11 Foot is a real issue. However, AEDC will likely be more competitive if NASA implements full-cost recovery at the 11-Foot as planned, spreading the full operating costs of the facility over the year's users through a full-cost transfer price.

Another issue to consider is whether it makes sense to require a backup (such as the Ames 11-Foot) to the AEDC 16T. Both the Ames 11-Foot and the Langley 16TT have serious deficiencies such as a lack of propulsion simulation and low Rn, respectively. Major issues remain with maintaining adequate support staff expertise at deactivated (or unused standby) facilities.

Langley National Transonic Facility

The NTF provides a unique very-high-Rn (i.e., flight-Rn) capability for all vehicle sizes. NTF should be desired and requested by researchers and developers alike if development risks (both technical and financial) are to be minimized for advanced aerodynamic technology concept implementations. It is an excellent research facility, with a knowledgeable operating and research staff that has reproduced a number of flight "surprises" in controlled, instrumented situations. NTF also has the potential for offering productive air-only high-Rn testing.

However, NTF productivity is less than desired at ambient and cryogenic testing conditions; this productivity issue would result in excessive design cycle time if required for production vehicle development. NTF has no propulsion simulation capability. Serious model dynamics issues and limitations at cryogenic temperatures and higher angles of attack have occurred with a number of test configurations.

Despite its world-class high-Rn capabilities, NASA needs to develop and validate viable solutions to the (previously encountered) model dynamics limitations at cryogenic temperatures. The agency also should determine whether improved (i.e., needed) productivity in air-only conditions is achievable.

Needed and desired NASA research topics requiring the use of NTF should be established. What are appropriate vehicle class targets? Are potential recipients of advanced technology receptive to eventual implementation? Are potential (research) developments viable in the current lean aeronautic-budget environment?

NASA should put into perspective the current user denial of the need for high-Rn testing as evidenced by current low utilization of high-Rn facilities. In addition to documented differences between data obtained at low Rn versus high Rn (e.g., Curtin et al., 2002), there are numerous documented examples for transport aircraft as well as an ample history of costly flight surprises with tactical aircraft. Consider, for example, misestimates of the cruise Mach number for the Boeing 777 (preventing the missed opportunity to trade speed for range or other trade-offs)[2] and the cruise drag predictions of the C-141 and C-5 (resulting in significant fuel cost increases).[3]

Figure 4.2 shows that NTF utilization has been consistently high in recent years. With the scheduled closure of the Langley 16TT and the air-only augmentation of NTF, utilization is anticipated to remain high—almost to the point where access may become an issue.

Special-Purpose Transonic WTs

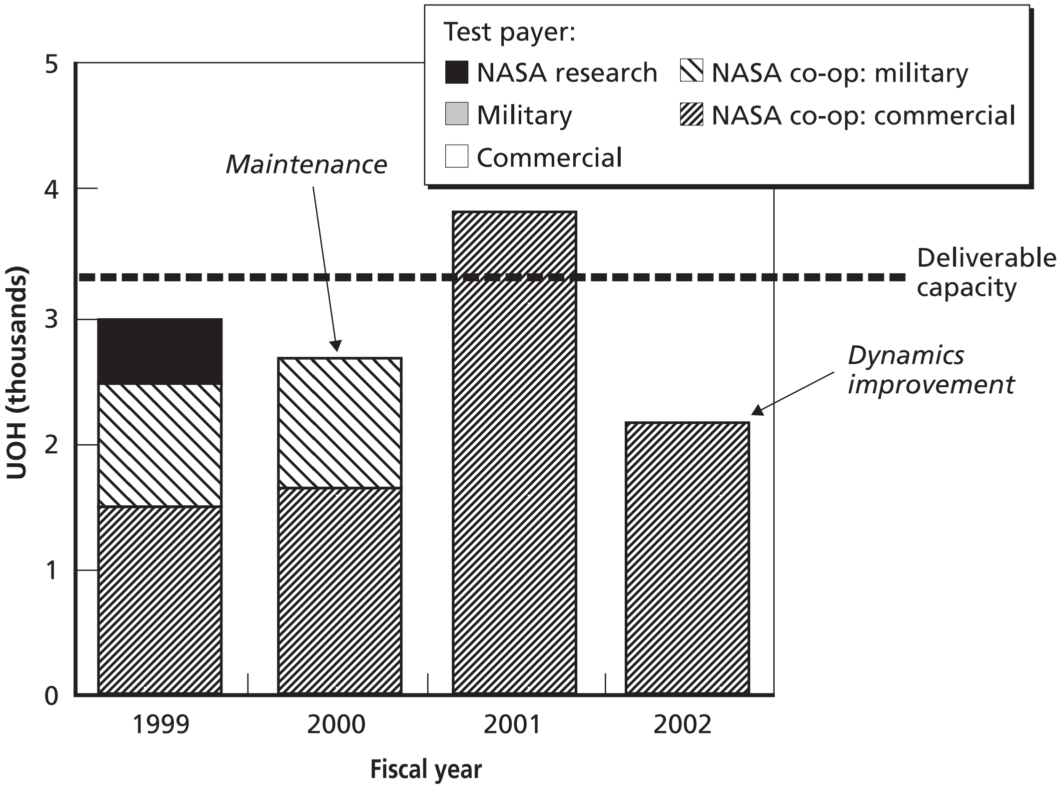
Langley Transonic Dynamics Tunnel

The Langley TDT is a unique national resource utilized and required for the testing of aeroelastically scaled models needed to investigate and establish the transonic flutter characteristics for most types of air vehicles operating in this speed regime. Its large test section size and use of a heavy (high-molecular-weight) gas (i.e., Freon) makes it possible to satisfy frequency scaling requirements with models that have the required strength to survive in the tunnel and, at the same time, attain noticeably higher (closer to flight values) Rn—i.e., by a factor of three (McMasters, 1988)— than could be achieved in air. There also exists a broad and strong (likely) user-stated need for this facility for any new air vehicle programs. While

[2] Discussed at the NASA/DoD Flight Prediction Workshop in November 2002.

[3] See Wahls (2001) and Crook (2002). Information also taken from the unpublished discussions at NASA/DoD Flight Prediction Workshop in November 2002.

Figure 4.2
NTF Historical Utilization by Test Payer



SOURCE: NASA Langley.
RAND *TR134-4.2*

the future utilization for this facility will be less than in the past because of the reduced number and frequency of actual production air vehicle launches in the United States, it is still needed to enable the design of viable low-risk and effective configurations. While CFD-based methods presently provide some very useful insights, foreseeable CFD improvements will not eliminate the requirement for this facility (for at least two decades and likely more). The only other comparable transonic dynamics facility is at ONERA in France, but most U.S. users do not consider it to be a viable alternative to the TDT for filling U.S. needs.

Two issues have been raised concerning the TDT. First, the maximum Mach number attainable in the TDT (i.e., 1.2) is not as high as desired (1.5) by some vehicle designers. A representative working group should be established to determine whether this maximum speed should or could be practically raised.

More importantly, there are potentially significant unknowns regarding the appropriate interpretation of test results obtained with a heavy gas, such as Freon, whose ratio of specific heats (gamma = 1.1) is not that of air (gamma = 1.4). Somewhat inaccurate correction models are currently being employed to compensate for the differences in gamma,[4] but

[4] While approximate inviscid (i.e., having negligible viscosity), small-disturbance transonic similarity theory corrections (Liepmann and Roshko, 1957, pp. 252–262) are presently used in an attempt to account for first-order compressibility and Mach number differences. It has been shown, however, by Anderson (1991) that such corrections are not really applicable when viscous effects are involved, which is the norm with typical critical transonic flow situations involving shock-

determining the degree and magnitude of these inaccuracies and their consequences needs to be better understood. To this end, it is strongly recommended that NASA initiate a thorough study and correlation of existing comparisons of TDT versus flight flutter characteristics and corresponding lessons learned for the range of air vehicles that have used the TDT or are anticipating using it in the foreseeable future. Once this has been accomplished, further studies or technology developments can be defined to guide a more effective utilization of the TDT with the intent of minimizing flight risks, uncertainties, and excessive conservatism.

Glenn 8×6-Foot Propulsion Wind Tunnel

The Glenn 8×6-Foot PWT is NASA's only transonic propulsion WT. It has an excellent Mach range and strong propulsion simulation capabilities.

However, the 8×6-Foot has low-Rn capabilities, which can limit its propulsion testing in certain applications. It cannot be viewed as a general-purpose facility because it has no force measurement capabilities and is not an effective backup to the AEDC 16T.

Langley 16-Foot Transonic Tunnel

The Langley 16-Foot Transonic Tunnel (16TT) is currently scheduled for closure but has had a long history of significant contributions by NASA Langley researchers to various U.S. tactical aircraft designs. It has been used as backup to AEDC 16T because of its propulsion simulation capabilities. The Langley 16TT has been very affordable for research investigations, since the AEDC 16T generally is not affordable except for production design and validation. Despite the closure decision, the Langley 16TT has been highly utilized by NASA and military programs (see Figure 4.3), often because of its ready availability and low cost.

However, the Langley 16TT is a low-Rn facility. It has poor flow quality (i.e., it is often referred to as a "4-foot" tunnel, since only about 4 feet of the 16-foot cross-section has good flow quality).

Is the Langley 16TT required as a backup to AEDC 16T for propulsion simulation testing? It is certainly more appropriate than the Glenn 8×6-Foot, but is a backup necessary for the AEDC 16T? How can NASA maintain an effective, maintained, and available support staff at a mothballed or standby facility?

If the closure decision for the 16TT were reconsidered, NASA would have to identify established or potentially viable research objectives requiring the use of the Langley 16TT—a low-Rn facility. Does NASA have any obligation to enable an affordable research capability to the DoD? If so, who should support it?

AEDC 4-Foot Transonic Wind Tunnel

The AEDC 4-Foot Transonic Wind Tunnel offers unique store separation and propulsion testing capabilities for smaller vehicles and missile investigations, thus providing a special-purpose technical capability that avoids the excessive costs of using the AEDC 16T for smaller vehicles.

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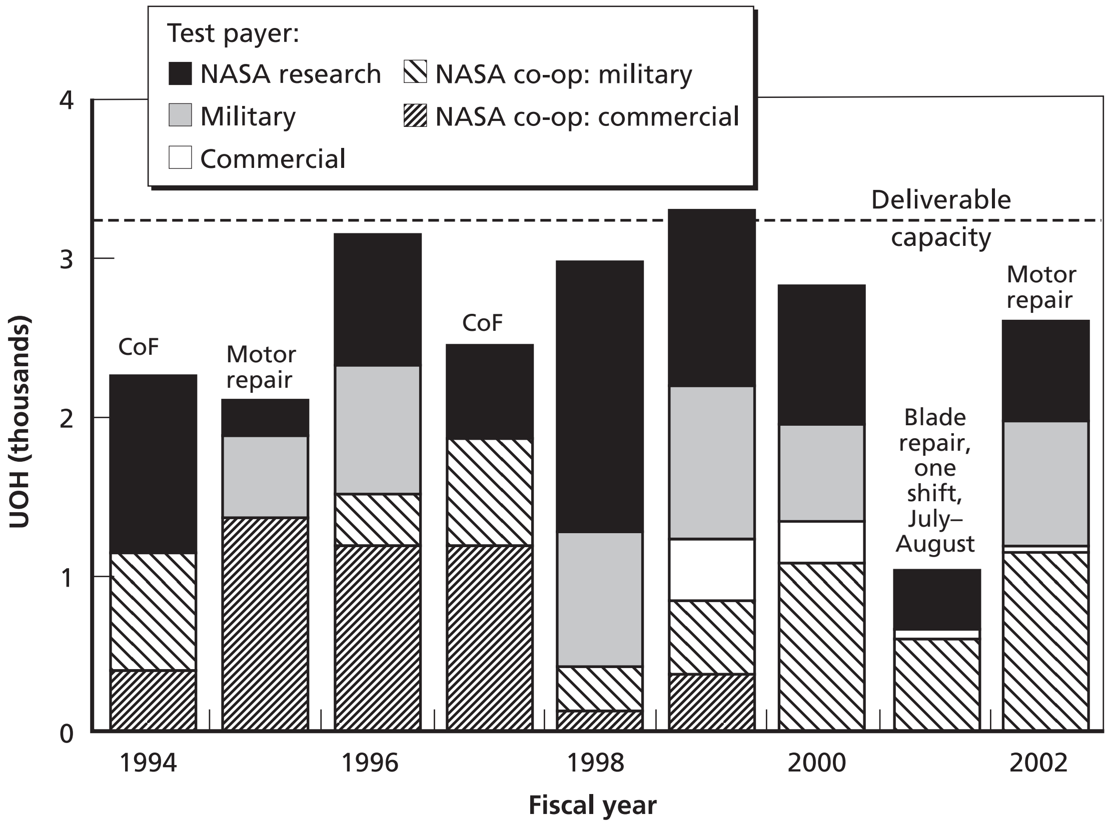
boundary-layer interactions where strong viscous effects are often dominating. It has been established (Anderson, 1991; Anders, Anderson, and Murthy, 1999) that viscous characteristics (e.g., transition, boundary layer growth rates, separation onset and progression characteristics) are different (from air) with a heavy gas, and it is expected that such boundary layer and viscous characteristics would be particularly influential in determining any unsteady flutter characteristics.

Figure 4.3
Historical Utilization of the Langley 16TT by Test Payer



SOURCE: NASA Langley.
RAND *TR134-4.3*

Conclusions and Recommendations for Existing Transonic WTs

Unlike subsonic WTs, the United States (with AEDC 16T and Ames 11 Foot) has *the* two premier high-productivity, high-Rn general-purpose transonic WTs in the world. However, several factors have combined to cause a sizable overcapacity in this category. There has been a much-reduced frequency of full-scale *production* launches for new (especially manned) aeronautic vehicles (recall Figure 2.1). High-Rn testing generally is not considered affordable for R&D with today's lean aeronautic research budgets. CFD has led to significant reductions in required transonic testing for transport aircraft. This has led to some notable tendencies to revert to lower-Rn testing for configuration development at transonic conditions to reduce development costs.

The obvious casualty of this overcapacity has been the Ames 11-Foot. AEDC 16T definitely has superior technical capabilities and is viewed (without exception) as technically acceptable alternative to the 11-Foot (but the converse is not true). The only reservations expressed by users with regard to using the AEDC 16T in lieu of the Ames 11-Foot involve its *availability* and *cost*. Considering the relatively near-term run out of the JSF testing requirements, though, any such availability difficulties appear to be minimal in the near term. Any consideration regarding a loss of the Ames 11-Foot would need some prior agreement between the DoD and NASA regarding potential NASA access to the AEDC 16T if and when needed.

The nation also has a premier very-high-Rn facility in the NTF, although the facility has model dynamics and productivity issues and is somewhat inferior to the next-generation ETW in Germany. Productivity limits the use of NTF for collecting large amounts of very-high-Rn T&E data, but the facility is considered invaluable for verifying extrapolation models from low-Rn tests, selected R&D activities, and difficult problems encountered during flight.

For the three lower-Rn NASA transonic facilities (the Glenn 8×6-Foot, Langley 16TT, and Langley TDT), similar actions recommended in the subsonic WT assessment are again needed before any permanent decisions on the status of these facilities are made. These recommendations include establishing a clear and binding relationship between NASA and the DoD regarding roles and responsibilities in operating (presently) underutilized NASA facilities mostly needed by the DoD. NASA (with inputs from the DoD) needs to carefully define viable topics and receptive vehicle categories for the agency's research and then determine what facilities are needed to support and transition this research to production. Presumably, DoD research needs will be defined as well.

These facility decisions should not be made without regard for categories of testing needs that may result from unforeseeable research breakthroughs or if the current budgetary deemphasis on aeronautics is reversed. WTs are research tools that take from 10 to 20 years and millions of dollars to construct, let alone the years involved in developing a knowledgeable and skilled operating workforce. Those tools should not be discarded carelessly based on short- or even medium-term funding trends, which have historically varied.

CHAPTER FIVE

Supersonic Wind Tunnels

Here we describe our analysis of the supersonic wind tunnels in light of our analysis of testing needs. The supersonic WTs studied are those with a Mach range of 1.5–5.0 and test cross-sections of 2 feet or more (in at least one dimension).

Table 5.1 presents an overview of the special capabilities and shortcomings of the key NASA, DoD, for-hire, industry, Canadian, and European supersonic WTs. As with the lower-speed facilities, these tables present a summary of the findings from our analyses of the tunnel specifications and the responses received from our questionnaires to the user community. This summary conveys the general pros and cons for these facilities and the complex nature involved in selecting a facility for a certain testing need rather than a comprehensive identification of all the technical factors and details for each facility. Additional technical specifications of these facilities, and the facilities' Web sites, can be found in Appendixes F and G.

The special capabilities identified in Table 5.1 include high or moderate Rn, propulsion simulation, store separation simulations, flutter, and good speed ranges. The United States has good moderate-Rn supersonic facilities, although the current Mach range for some facilities are inadequate. Most of the non-NASA, non-AEDC facilities are blow-down facilities, which can present some limitations when longer runs are desired. However, most data can be obtained during the blow-down cycles, and model changes can be faster in some blow-down facilities.

Table 5.2 presents a summary of the advocacies received from current NASA programs, DoD representatives, and industry representatives for the three existing supersonic WTs at NASA. The two supersonic facilities at AEDC provide important user context, so we included their advocacies as well to give perspective. The advocacy data are illustrative and informative, rather than comprehensive and dogmatic. As with the advocacies shown before, we note that such strategic advocacies are enlightening but do not necessarily predict future utilizations.

Table 5.1
Special Capabilities and Shortcomings of Existing Supersonic WTs

				Special Capabilities						Shortcomings			
Owner	WT	Mach Number	Blow-Down?	High Rn	Moderate Rn	Propulsion Simulation	Store Separation	Flutter	Good Mach Range	Low Rn	No Force Testing	Poor Mach Range	Too Small for Some
Ames	Unitary 9×7-Foot	1.5–2.55			√							X	
Langley	Unitary 4-Foot	1.5–2.9											X
		2.3–4.6			√				√				
Glenn	10×10-Foot	2.0–3.5				√				X	X		
AEDC	16S Propulsion	1.5–4.75[a]			√	√	√		√[a]			X[a]	
	VKF Tunnel A	1.5–5.6			√		√		√				X
Allied Aerospace	7-Foot Trisonic	0.3–3.5	X		√								
Boeing	4-Foot Polysonic	0.3–5.0	X		√				√				X
Lockheed Martin	4-Foot (LTV) HSWT	0.4–4.8	X		√		√		√				X
NRC/IAR	5-Foot Trisonic	1.1–4.25	X		√				√				X
BAE	4-Foot at Wharton	?	?									?	X
DNW	1.2M SST	1.2–4.0	X		√		√						X
ONERA	S2 at Modane (1.94×1.75M)	0.1–3.1								X		X	X
FOI	1.5M HSWT	1.3–2.0	?		√							X	X

[a]See the subsection on the AEDC 16S for a detailed discussion of its Mach range, which is currently less than 4.75.

Table 5.2
Advocacies for Existing Supersonic WTs

	Ames	Langley	Glenn	AEDC	
	9×7-Foot UPWT	4-Foot UPWT	10×10-Foot	16S PWT	VKFA
NASA					
Research and specific programs		√	√		
DoD					
Air Force ASC				√	
Army (UAV and missiles)					√
NAVAIR	√	√	√	√	
Industry					
Boeing					
–Commercial (transport A/C)	√		√	√	
–Tactical A/C		√			√
–S. Calif (high-speed vehicles)	√	√	√	√	
–Hypersonic programs	√				
Gulfstream (business jets)[a]					
Lockheed Martin	?	No		√	
Northrop Grumman	√		√	√	
Raytheon A/C [a]					
Raytheon Missiles			√		√

SOURCE: Responses to RAND's questionnaire, 2003.
[a]Very generic response—no specific tunnels mentioned.

There has been little recent active supersonic R&D and production apart from the F-22, JSF, space access, and hypersonic missile programs. Some models extrapolating performance from transonic speeds have reduced the use of supersonic tunnels for some vehicles for which we have prior expertise (e.g., fighters). Nevertheless, many users recognized that supersonics is still an important area that requires the country to retain a strong testing capability. Extrapolation models from transonic testing will likely lose their validity when different supersonic concepts and vehicles are explored, and space access programs will need supersonic testing.

Supersonic WT Health Ratings and Summary Descriptions

Table 5.3 summarizes our analysis of NASA (and selected DoD) supersonic WTs—both general-purpose tunnels and those with special-purpose technical capabilities. We gave each tunnel an overall health rating, using the levels from Table 3.4 in Chapter Three.

Table 5.3
Health Ratings and Summaries of Existing Supersonic Tunnels

Facility	Health	Summary
General-Purpose		
Ames 9×7-Foot UPWT	Poor	• High Rn; compatible with Ames11-Foot • Maximum Mach 2.5 a concern; no propulsion simulation capability • Potential users have prior databases; supersonic business jet advocacy • Limited utilization; cost a concern
AEDC 16S	OK	• Compatible with AEDC 16T • High Rn; has propulsion simulation capability • Mach range (as restored) a plus • Size overkill for some applications • Cost a concern except for production and validation • Look at feasibility of operating at low subsonic speeds to augment subsonic WTs
Special-Purpose		
Glenn 10×10-Foot (propulsion)	Poor	• Propulsion simulation, but low Rn and no force testing • Speed up to Mach 3.5 a plus (compared with AEDC 16S), but 2.0 minimum is not helpful • Backup facility (viable concept?)
Langley UPWT 4-Foot (smaller vehicles)	OK	• Excellent Mach range • Much more cost effective for these applications than AEDC 16S and ARC 9×7-Foot • Continuous flow a plus compared with other 4-Foot tunnels • Need to define viable research objectives for this facility
AEDC VKF A (continuity to hypersonic speeds)	Fair	• Excellent (best) Mach range (1.5–5.5) needed for some applications • Relatively small, 40-Inch size is a limitation for a number of applications

General-Purpose, High-Rn Supersonic WTs

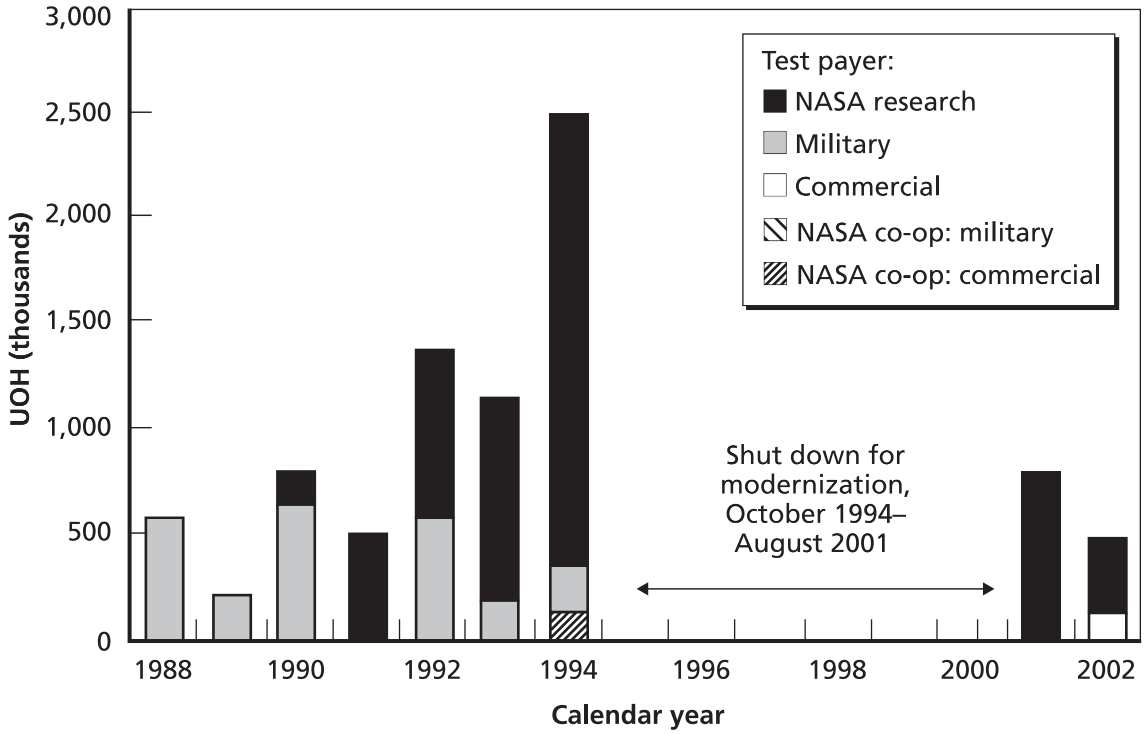
Ames 9×7-Foot Supersonic Unitary Plan Wind Tunnel

The supersonic Ames 9×7-Foot UPWT is a high-Rn test section compatible with the Ames 11-Foot. Potential users have prior databases and experience with the 9×7-Foot, and the supersonic business jet community has voiced advocacy for the facility.

However, the maximum Mach number of only 2.5 is a limitation and concern, and the facility has no propulsion simulation capability. Cost is also a concern, since there is no shared support from the center for the facility, so users will have to bear the full annual operating plus marginal costs for the few tests they conduct.

Figure 5.1 shows that utilization at the Ames 9×7-Foot has been low since operation resumed after the extended shutdown from October 1994 through August 2001 for facility modernization, although the levels in 2001 and 2002 have been similar to those shown prior to the shutdown (except for 1994, when a large number of tests were put through before the facility was shut down).

Figure 5.1
Historical Utilization at Ames 9×7-Foot Supersonic UPWT by Test Payer



SOURCE: NASA Ames.
RAND *TR134-5.1*

AEDC 16-Foot Supersonic Wind Tunnel

The DoD's AEDC 16S is the premiere U.S. general-purpose supersonic WT. It is a high-Rn facility with propulsion simulation capabilities and is compatible with the AEDC 16T in size.

Because of the mothballing during periods of disuse, the functional Mach range of the 16S reflects the needs of the testing needs at the time, maintenance to bring online additional equipment required for higher Mach numbers is being performed only as needed. At the time of this study, the functioning Mach range had been seriously limited to 1.6–2.2. According to AEDC, however, maintenance to extend the maximum Mach to 2.7 is planned for tests in FY2005—and to Mach 3.4 for test in FY2006. The advertised maximum of 4.75 could be achieved with additional maintenance. The 16S was originally designed to achieve Mach 6 but has never operated above 4.5. AEDC believes the 16S may have enough pressure ratio to achieve Mach 6, but further analysis is required to know for certain.

However, the size of the 16S is overkill for some applications, and cost is a real concern except for large production and validation programs.

As with the 16T, AEDC should continue to look at the feasibility of operating the 16S at low speeds to augment the U.S. deficiency in subsonic WT capabilities.

Small High-Rn Supersonic WTs

Langley 4-Foot Supersonic Unitary Plan Wind Tunnel

The Langley 4-Foot UPWT is a special-purpose tunnel for smaller supersonic vehicles. It has excellent Mach range and is much more cost-effective for these applications than the AEDC 16S and the Ames 9×7-Foot. Continuous flow can be a plus compared with other 4-foot blow-down tunnels.

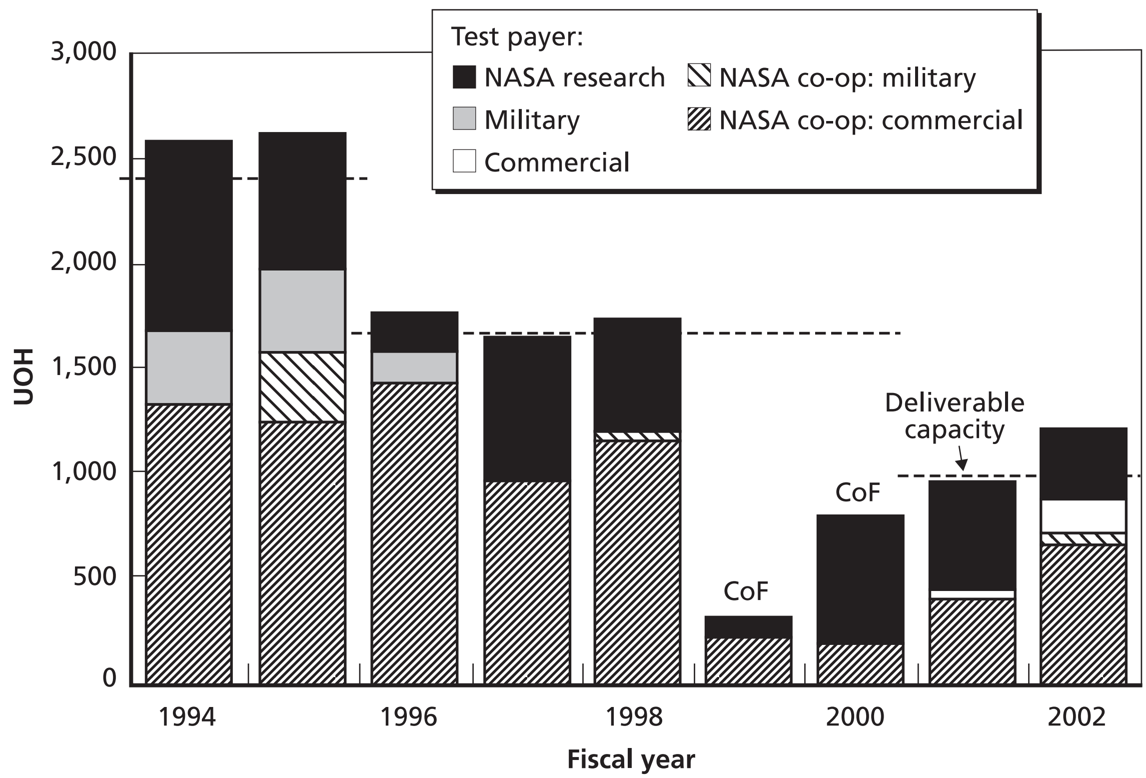
Figure 5.2 shows that the historical utilization at the Langley 4-Foot has been relatively strong over the past decade and moderate in the past two years. Our biggest concerns for the facility are the continued existence of shared support to keep the facility alive during lower-utilization years and the need for NASA to define viable supersonic research objectives for it.

Special-Purpose Supersonic WTs

Glenn 10×10-Foot Supersonic Wind Tunnel

The Glenn 10×10-Foot Supersonic Wind Tunnel is a special-purpose tunnel for propulsion simulations. While the 10×10-Foot's maximum speed of Mach 3.5 is a plus compared with

Figure 5.2
Historical Utilization at Langley 4-Foot Supersonic UPWT by Test Payer



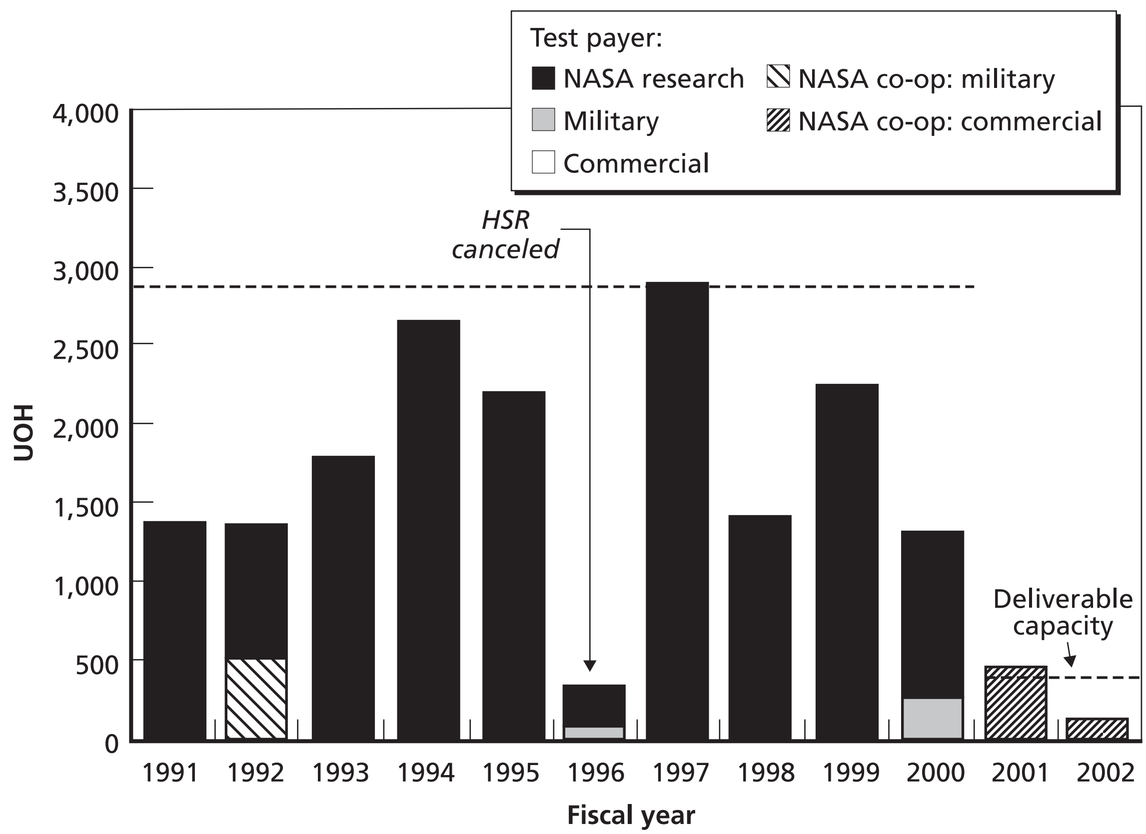
SOURCE: NASA Langley.
RAND *TR134-5.2*

the AEDC 16S, its minimum Mach of only 2.0 is a limitation because it leaves a gap between the maximum Mach number of most transonic facilities. Also, the facility has a low Rn and no force testing capability, limiting some of its applications and preventing it from being a general-purpose facility.

It is unclear whether the 10×10-Foot can be viewed as an effective backup to the AEDC 16S because of the concerns expressed above about the viability of the facility backup concept and the workforce issue.

Figure 5.3 shows the historical utilization of the 10×10-Foot by test payer. The utilization over the past decade has been reasonably good, although it has been falling off in the last two years. Interestingly, these two years have also shifted toward cooperative research rather than pure NASA research testing. This is not necessarily bad as cooperative research leverages external resources to extend NASA's research investments, but the testing levels have been lower.

Figure 5.3
Historical Utilization at Glenn 10×10-Foot Supersonic Wind Tunnel by Test Payer



SOURCE: NASA Glenn.
RAND *TR134-5.3*

AEDC von Karman Gas Dynamics Facility Wind Tunnel A

The AEDC von Karman Gas Dynamics Facility Wind Tunnel A (VKF A) is used for continuity to hypersonic speeds. It has an excellent—in fact, the best—Mach range (1.5–5.5) needed for some applications, although its relatively small, 40-inch size is a limitation for a number of applications.

Conclusions and Recommendations for Existing Supersonic WTs

The AEDC 16S and Ames 9×7-Foot are clearly the preeminent supersonic WTs in the world today, but both sit idle much of the time because of current low demand from today's production vehicles. Even the JSF testing schedule for these facilities was withdrawn. Unquestionably, there is a surplus capacity needing to be dealt with in a rational way that preserves tools for the long term.

Although these facilities are the two dominant general-purpose supersonic WTs in existence, both leave something to be desired. The AEDC 16S is clearly superior in size, in having a propulsion simulation capability, in its compatibility with AEDC 16T, and in having the potential to be upgraded to provide a meaningful high-Rn subsonic testing capability. Unfortunately, the 16S's current maximum speed of Mach 2.2 is a big concern; the 16S used to run up to Mach 4.0. Being able to run only at Mach 2.2 leaves a big speed range unexplored for hypersonic vehicles, and at least one organization expressed the belief that, while extrapolations from Mach 1.5 were considered acceptable for current supersonic tactical fighters, future supersonic vehicles may require actual WT testing up to Mach 4.0.

The Ames 9×7-Foot is not much better, having a maximum Mach of only 2.5 now that the Ames 8×7-Foot leg is no longer available. However, because the Ames 9×7-Foot does not have a prolusion simulation capability, is tied in with the endangered and lower-ranked Ames 11-foot Transonic Tunnel, and is too small for some applications, it is clearly in the weaker position and needs consideration.

If the Ames 9×7-Foot (together with the Ames 11-Foot) is closed, there needs to be a high-level, binding, long-term agreement between NASA and the DoD regarding access and cost concerns with the AEDC 16S.

In the special-purpose facility category, the Langley 4-Foot UPWT is clearly the premier facility in this size category (relative to all the 4-foot blow-down WTs). It is more cost effective for smaller vehicles and for NASA (and DoD) research purposes. It is important, however, that viable, attractive, and then properly funded NASA (and DoD) research topics be identified to keep this area active. This identification needs to address what practical vehicle categories are important to pursue in the supersonic speed regime.

The Glenn 10×10-Foot, despite its propulsion simulation capability, is only a low-Rn facility, cannot do force testing, and requires the (poorly ranked and smaller) 8×6-Foot Transonic Wind Tunnel (with similar deficiencies) to cover Mach range below 2.0. Thus, the Glenn 10×10-Foot is not an effective backup to the AEDC 16S. It does provide a unique propulsion simulation capability within NASA, up until quite recently has had consistent utilization, is local to the Glenn propulsion researchers, and can handle hot propulsion simulation.

CHAPTER SIX

Hypersonic Wind Tunnels

Here we describe our analysis of the hypersonic wind tunnels in light of our analysis of testing needs. The hypersonic WTs studied are those with a Mach range of 5.0 or more with test cross-sections of 1 foot or more (in at least one dimension).

Table 6.1 presents an overview of the special capabilities and shortcomings of NASA and DoD facilities as well as selected key commercial facilities (e.g., hypersonic tunnels at Veridian and Calspan-University of Buffalo Research Center [CUBRC]) that are truly critical for research and national security reasons. Additional technical specifications of these facilities, and the facilities' Web sites, can be found in Appendixes F and G. The remaining facilities—those commercially run (e.g., Aero Systems Engineering [ASE]) and those run by the aerospace industry (e.g., Boeing and Lockheed Martin)—are market driven, and their operational focus may not coincide with research or national security issues.

The special capabilities identified in Table 6.1 include high Mach numbers, aerodynamic heating, store (and stage) separation, boundary-layer transitions, research capabilities, real gas effects, and reasonable cost. Shortcomings include weak user advocacy, low productivity, size constraints, and short run-time limitations.

The Langley hypersonic tunnel series (20-Inch CF4, 20-Inch Air, and 31-Inch Air) are the most cost effective for R&D but have size limitations when compared with the more expensive AEDC VKF tunnels. The Veridian (Calspan) and CUBRC LENS facilities are generally constrained in run times.

Most of the hypersonic WTs are unique, although the Langley 20-Inch and 31-Inch Air tunnels are comparable to the AEDC VKF B and C facilities, respectively. Also, the Veridian 48-Inch and 96-Inch shock tubes are comparable to the CUBRC LENS I facility.

Table 6.2 presents a summary of the advocacies received from current NASA programs, DoD representatives, and industry representatives for the hypersonic WTs.[1]

The users rated approximately *75–80 percent* of available facilities *essential* for hypersonic testing. Exceptions were the ASE Channel 9 facility and the AEDC hypervelocity Impact Range S1 (although the latter's primary purpose is not hypersonic aerodynamics testing and as such should not be interpreted as a negative for that facility).

There has been a recent upsurge in hypersonics research. Because many of the hypersonic programs are still in their early planning stages (e.g., at DARPA), it is difficult to obtain quantitative estimates of future need; however, we were able to obtain qualitative advocacy and needs statements from these programs.

[1] The advocacy data are illustrative and informative rather than comprehensive and dogmatic. As with the advocacies shown before, we note that such strategic advocacies are enlightening but do not necessarily predict future utilizations.

Table 6.1
Special Capabilities and Shortcomings of Existing Hypersonic WTs

			Special Capabilities							Shortcomings				
Owner	Tunnels	Mach No. Range	High Mach	Aero-heating	Store and Stage Separation	Boundary Layer Trans	Research	Real Gas Effects	Lower Cost	Weak User Advocacy	Poor Productivity	Size	Run Time	Comparable Facilities
Langley	20-Inch CF4	6.0					√	√	√		X	X		None
	20-Inch Air	6.0		√	√	√	√		√		X	X		VKF B
	31-Inch Air	10.0		√			√		√			X		VKF C
AEDC	VKF Tunnel A	1.5–5.6		√	√									None
	VKF Tunnel B	6 or 8		√	√									None
	VKF Tunnel C	10		√	√									None
	Hypervelocity Wind Tunnel 9	7, 8, 10, 14, 16.5	√	√										None
	Hypervelocity Range/Track G	To 24k fps	√				√							None
	Hypervelocity Impact Range S1	To 28k fps	√				√			X				None
Army/ CUBRC	LENS I	8–18	√	√									X	None
	LENS II	4.5–8		√									X	None
ASE	Channel 9: 20-Inch	7, 11, 14	√				√			X				None
Veridian	Calspan 48-Inch Shock Tube	5.0–18	√	√									X	Lens I
	Calspan 96-Inch Shock Tube	7.0–19	√	√									X	Lens I

Table 6.2
Advocacies for Existing Hypersonic WTs

	Langley			AEDC						Army/CUBRC		ASE	Veridian	
	20-Inch CF4	20-Inch Air	31-Inch Air	VKF A	VKF B	VKF C	Tunnel #9	Range/ Track G	Impact Range S1	LENS I	LENS II	Channel 9: 20-Inch	48-Inch Shock	96-Inch Shock
Mach Range:	6.0	6.0	10.0	1.5–5.6	6 or 8	10	7, 8, 10, 14, 16.5	to 24k fps	to 28k fps	8–18	4.5–8	7, 11, 14	5.0–18	7.0–19
NASA														
NASA	√	√	√											
DoD														
ASC	√			√	√	√	√			√	√			
MDA				√	√		√			√	√		√	√
Army		√	√	√	√	√								
DARPA								√						
Industry														
NGC				√	√	√	√			√	√		√	√
Air Force	√													
Boeing	√	√	√	√	√	√	√			√	√		√	√
Comparable Facilities	None	AEDC VKF B	AEDC VKF C	None	None	None	None	None	None	None	None	None	LENS I	LENS I

SOURCE: Responses to RAND questionnaire, 2003.

Hypersonic WT Health Ratings and Summary Descriptions

Table 6.3 summarizes our analysis of NASA (and selected DoD and commercial) hypersonic WTs—both general-purpose tunnels and those with special-purpose technical capabilities. We gave each tunnel an overall health rating using the levels from Table 3.4 in Chapter Three.

General-Purpose Hypersonic WTs

Langley Hypersonic Wind Tunnels: 20-Inch Mach 6 CF4, 20-Inch Mach 6 Air, and 31-Inch Mach 10 Air

The Langley 20-Inch Mach 6 CF4, 20-Inch Mach 6 Air, and 31-Inch Mach 10 Air are three of the four tunnels in the Aerothermodynamic Facilities Complex used for basic fundamental flow physics research, aerodynamic performance measurements, and aeroheating assessment, optimization, and benchmarking of advanced space transportation vehicles.[2]

These tunnels are the predominant choice for "preliminary design" and some real gas effects. Together, they cover the range of speeds needed to understand how a vehicle will

Table 6.3
Health Ratings and Summaries of Existing Hypersonic WTs

Facility	Health	Summary
General-Purpose		
Langley: 20-Inch M6 CF4, 20-Inch M6 Air, and 31-Inch M10 Air	Good	Choice for "preliminary design" and some real gas effects Good for research Blow-down facilities Aeroheating, some separation capabilities Real gas effects and low cost Strongest customer concern: *productivity*
AEDC: VKF A, B, and C; Tunnel #9	Good	Choice for "production testing" as opposed to "preliminary design" Best overall capability Continuous flow; generally large scale Good stage, store separation capabilities and some materials testing High Mach capability No strong customer concerns except *cost* and *availability*
Special-Purpose		
Army/CUBRC: LENS I and II	Good	High Mach capability Good for aeroheating Customer choice for certain applications Possible minus: *duration*
ASE Channel 9 (research, dynamics)	OK	High Mach capability Good for research Some dynamic testing capability
Veridian: 48-Inch and 96-Inch Shock Tubes	Good	High Mach capability Good for aeroheating Customer choice for certain applications Possible minus: *duration*

[2] The fourth tunnel is the 15-Inch Mach 6 HTT for hypersonic propulsion integration testing discussed below with the next set of facilities.

behave. The three tunnels are all blow-down facilities, provide aerodynamic heating and some separation capabilities, are relatively low cost, and are good for research. The CF4 provides real gas effects. The strongest concern among users was the tunnels' productivity.

AEDC von Karman Gas Dynamics Facility Wind Tunnels

The three AEDC VKF tunnels A, B, and C are predominantly the facilities of choice for "production testing," as opposed to "preliminary design." They provide the best overall hypersonics capability. They have continuous flow (as opposed to blow-down at NASA), are generally large scale, have good vehicle stage and store separation capabilities, provide some materials testing, and have a speed capability greater than Mach 10.

There were no strong customer concerns for the VKF facilities except cost and availability.

AEDC Tunnel 9

AEDC Tunnel 9 provides aerodynamic simulation at Mach numbers 7, 8, 10, 14, and 16.5, completing the upper Mach range for AEDC. The intermittent operation of up to 15 seconds allows for an angle-of-attack sweep or flow-field survey during the flow period.

Special-Purpose Hypersonic WTs

AEDC Hypervelocity Range/Track G and Hypervelocity Impact Range S1

We included the AEDC Hypervelocity Range/Track G and Hypervelocity Impact Range S1 to provide some context based on their speed capabilities, although we did not include the full set of such ranges (or uses for such ranges) in this study.

Army CUBRC Large-Energy National Shock Tunnels I and II

The Army's CUBRC LENS Tunnels I and II are a pair of 8-foot cross-section, short-duration, high-enthalpy shock tunnels that share some common equipments.[3] Together, these facilities offer high Mach capability and are good for aerodynamic heating tests. They are customer choice for certain applications. LENS Leg I offers Mach numbers from approximately 8 to 18. LENS Leg II runs at more modest Mach numbers (about 4.5–8.0). The short run times for LENS I and II (30 milliseconds and 100 milliseconds, respectively) could be a minus for certain applications.

Aero Systems Engineering Channel 9

The ASC 20-Inch Channel 9 hypersonic WT offers high Mach capability (Mach numbers 7, 11, and 14), is good for research, and has some dynamic testing capability.[4]

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[3] LENS I and II are government-owned test facilities operated by CUBRC for the U.S. Army Aviation & Missile Command to support the development of missile defense interceptors and advanced technology for the U.S. Department of Defense (see www.infofusion.buffalo.edu/cubrc_info/cubrc_info.htm, last accessed June 2004). CUBRC is an independent, not-for-profit multidisciplinary research partnership founded by Calspan (now Veridian Engineering Inc.) and the Research Foundation of the State University of New York.

[4] Channel 9 is part of the FluiDyne Aerotest Laboratory now owned and operated by ASE, a commercial company offering WT services.

Veridian 48-Inch and 96-Inch Shock Tubes

Veridian now operates the 48-Inch and 96-Inch Shock Tubes previously run by the CALSPAN Corporation. These facilities offer broad and high Mach capability and are good for aerodynamic heating tests. They are the customer choice for certain applications. A possible minus for these facilities is their short test duration capabilities.

Conclusions and Recommendations for Existing Hypersonic WTs

Nearly all existing hypersonic WTs are *essential* for the hypersonic RDT&E field that has seen a recent large upswing in active research on access to space vehicles and hypersonic missiles. The three NASA facilities (20-Inch Mach 6 CF4, 20-Inch Mach 6 Air, and 31-Inch Mach 10 Air) fill a necessary need for low-cost preliminary design work in which cost can be a factor in larger, more expensive facilities. It is true that similar conditions can be tested at AEDC facilities, but the cost of facilities and models is much higher. Therefore, the maturity of the project design governs the move to larger facilities.

At present, it is premature to advocate for new hypersonic wind tunnels, although future advances in R&D may produce specific needs for major facility upgrades or construction. The user community should be surveyed again in five years to determine progress and identify new needs.

CHAPTER SEVEN

Hypersonic Propulsion Integration Test Facilities

Here we describe our analysis of the hypersonic propulsion integration test facilities in light of our analysis of testing needs. The hypersonic propulsion integration test facilities studied are those with a Mach range of 5.0 or more, with test cross-sections of 1 foot or more (in at least one dimension).

Table 7.1 presents an overview of the special capabilities and shortcomings of NASA and DoD facilities as well as selected key commercial facilities (at ASE, Veridian, and CUBRC) that are important for research and national security reasons. Additional technical specifications of these facilities can be found in Appendixes F and G, the facility Web sites referenced within these appendixes, and Guy et al. (1996).

The special capabilities identified in Table 7.1 include high Mach numbers, total pressure, test duration, enthalpy level, aerodynamic heating, non-vitiated air,[1] and size. Shortcomings include weak user advocacy, vitiated air, low maximum Mach numbers, size constraints, and short run-time limitations.

The Langley facilities provide flight Mach number duplication from 3.5 to 8.0 (blow-down Scramjet Test Facility) and from 7 to 19 (Hypersonic Pulse Facility, or HYPULSE). These facilities have been in operation since the 1970s, accumulating data from approximately 4,000 tests of 22 scramjet designs through 2001. Tests have obtained data on engine flow path and on components such as inlets, nozzles, fuel injection, mixing, and combustion. The data have been used to derive and confirm design and analysis methods to establish engine and fuel system operational limits.

The Ames facilities have been mothballed and would require approximately $10 million to bring back online. They were used extensively on the NASP program and, in particular, to provide duration testing at high Mach numbers.

The Glenn HTF, the Langley 8-Foot HTT, and the AEDC APTU facilities operate at approximately the same high Mach number of about 7 (although a funded upgrade for the APTU scheduled for completion in FY2005 will raise its maximum Mach number to 8). The Glenn HTF is the only non-vitiated air facility of the three. The Langley HTT presently appears to have the most capability of the three.

The Veridian and CUBRC shock tubes and LENS I and II facilities offer high Mach number testing (up to 18 or 19). The HYPULSE facility (already mentioned) falls into this category as well.

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[1] The ability to have non-vitiated air in the facility provides a more realistic chemical composition without combustion byproducts that may interfere with hypersonic propulsion such as ramjets and scramjets. The importance of non-vitiated air in tests is an unresolved debate within the hypersonics propulsion community.

Table 7.1
Special Capabilities and Shortcomings of Existing Hypersonic Propulsion Integration Facilities

Owner	Hypersonic Propulsion Integration Test Facilities	Mach Number Range	Special Capabilities							Shortcomings				
			High Mach	Total Pressure	Test Duration	Enthalpy Level	Aero-heating	Non-Vitiated Air	Size	Weak User Advocacy	Vitiated Air	Run Time	Maximum Mach	Size
Langley	8-Foot HTT	5.0–7.0		√		√	√		√		X			
	Arc-Heated Scramjet	4.7–8.0				√		√						
	Combustion-Heated Scramjet	3.5–6.0				√					X		X	X
	Direct-Connect Supersonic Combustion	4.0–7.5				√				X	X			
	15-Inch Mach 6 High Temperature Tunnel	6.0								X			X	X
Ames	Direct-Connect Arc													
	16-Inch Shock Tunnel													
Glenn	HTF	5, 6, 7				√		√	√					
	PSL-4	6.0							√	X			X	
NASA/GASL	HYPULSE	7.0–21	√	√								X		X
AEDC	Aero and Propulsion Test Unit	2.2–7.2[a]					√		√		X			
	Arc-Heated H-3 Facility													
Army/ CUBRC	LENS I	8–18	√			√						X		
	LENS II	4.5–8							√			X		
ASE	Channel 9: 20-Inch	7, 11, 14	√											X
Veridian	Calspan 48-Inch Shock Tube	5.0–18	√			√						X		
	Calspan 96-Inch Shock Tube	7.0–19	√			√						X		

[a]According to AEDC, a funded upgrade to APTU scheduled for completion in FY05 will raise its maximum Mach number to 8.0.

Table 7.2 summarizes the advocacies received from current NASA programs, DoD representatives, and industry representatives for the hypersonic propulsion integration facilities.[2]

The users rated approximately *80 percent* of available facilities *essential* for hypersonic propulsion integration testing. Exceptions were the Glenn PSL-4 (for hypersonic testing, not the more general-purpose direct-connect propulsion testing that is discussed latter), the Langley Direct-Connect Supersonic Combustion Test Facility (DCSCTF), and the Langley 15-Inch Mach 6 High Temperature Tunnel.

Since many new hypersonics programs were still in their early planning stages (e.g., at DARPA), it was difficult to obtain quantitative estimates of their future need. However, those programs were able to provide qualitative advocacy and needs statements.

Hypersonic Propulsion Integration Test Facility Health Ratings and Summary Descriptions

Table 7.3 summarizes our analysis of NASA (and selected DoD and commercial) hypersonic propulsion integration test facilities. We gave each facility an overall health rating using the levels from Table 3.4 in Chapter Three. Note that PSL-4's health rating is relative to its use only for hypersonic propulsion integration, not as a general-purpose direct-connect propulsion simulation facility. We provide its rating for the latter in the next section.

Special-Purpose Hypersonic Propulsion-Integration Facilities

Langley Hypersonic Propulsion Integration Test Facilities and HYPULSE

The Langley hypersonic propulsion integration test facilities are a suite of facilities that, when including HYPULSE, cover the operational envelope for scramjet propulsion R&D with generally subscale models. The facilities consist of the following:

- Langley 8-Foot High-Temperature Tunnel (8-Foot HTT)
- Langley Arc-Heated Scramjet Test Facility (AHSTF)
- Langley Combustion Heated Scramjet Facility (CHSTF)
- Langley Direct-Connect Supersonic Combustion Test Facility (DCSCTF
- Langley 15-Inch Mach 6 High Temperature Tunnel (15-Inch M6 HTT)[3]
- HYPULSE Shock Tunnel.[4]

The Mach number and enthalpy range for these facilities appear to be adequate.

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[2] The advocacy data is illustrative and informative rather than comprehensive and dogmatic. As with the advocacies shown before, we note that such strategic advocacies are enlightening but do not necessarily predict future utilizations.

[3] The 15-Inch M6 HTT is the fourth tunnel in the Langley Aerothermodynamic Facilities Complex (rounding out the 20-Inch Mach 6 CF4, 20-Inch Mach 6 Air, and 31-Inch Mach 10 Air discussed in the hypersonic wind tunnel section).

[4] HYPULSE is located in Ronkonkoma, New York, and is owned by NASA but operated by the GASL Division of Allied Aerospace. Allied Aerospace was formed in 1999 by the acquisition of GASL Inc., Dynamic Engineering Inc., and Micro Craft Inc.

Table 7.2
Advocacies for Existing Hypersonic Propulsion Integration Test Facilities

	Langley					Ames		Glenn		NASA/GASL	AEDC		CUBRC		ASE	Veridian	
	8-Foot HTT	Arc-Heated Scramjet	Combustion Heated Scramjet	Direct-Connect SS Combustion	15-Inch M6 HTT	Direct-Connect Arc	16-Inch Shock	HTF	PSL-4	HYPULSE	APTU	Arc-Heated H-3	LENS I	LENS II	Ch 9: 20-Inch	48-Inch Shock	96-Inch Shock
Mach Range:	**5.0–7.0**	**4.7–8.0**	**3.5–6.0**	**4.0–7.5**	**6.0**			**5, 6, 7**	**6.0**	**7.0–21**	**2.2–7.2[a]**		**8–18**	**4.5–8**	**7, 11, 14**	**5.0–18**	**7.0–19**
NASA																	
NASA	√							√									
DoD																	
ASC	√					√	√			√	√	√	√	√			√
MDA											√		√	√	√		
Army	√									√			√	√			
DARPA	√										√						
Industry																	
NGC													√	√		√	√
Boeing	√	√	√			√		√		√	√	√	√	√		√	√

SOURCE: Responses to RAND questionnaire, 2003.
[a]According to AEDC, a funded upgrade to APTU scheduled for completion in FY2005 will raise its maximum Mach number to 8.0.

Table 7.3
Health Ratings and Summaries of Existing Hypersonic Propulsion Integration Facilities

Facility	Health	Summary
General-Purpose		
Langley 8-Foot HTT, Arc Scramjet, Combustion Scramjet, SS Combustion, 15-Inch M6 HTT, and NASA/GASL HYPULSE	OK	• Langley facilities with HYPULSE cover the operational envelope for scramjet propulsion research and development with generally subscale models • Biggest drawbacks: *size* and *duration* • The Mach number and enthalpy range appear to be adequate • Most have the disadvantage of vitiated air
Ames Direct-Connect	OK	• Capability for longer duration testing at velocities greater than 7,000 fps for modest investment • Benchmark data to anchor test data needed for modeling
Ames 16-Inch Shock	OK	• Integrated engine tests for benchmarking, good for research
Glenn PSL-4	Poor	• Very weak advocacy • *Size* and *speed* limited
Glenn HTF	Fair	• Unique non-vitiated capability; *size* and *speed* limited • Good advocacy, but low utilization endangering health given mothball policy
AEDC APTU and Arc-Heated H3	OK	• Generally similar to Langley facilities • Generally *size* and *speed* limited, limiting access to space and hypersonic missile propulsion development
Army/CUBRC: LENS I and II	Good	• High Mach capability • Excellent optics testing capability • Possible minus: *duration*
ASE Channel 9	Good	• High Mach capability, good for research
Veridian: 48-Inch and 96-Inch Shock Tubes	Good	• High Mach capability • Excellent optics testing capability • Possible minus: *duration*

The advocacy for the 8-Foot HTT is particularly strong. Many users viewed the HTT as a critical hypersonic resource at Langley. This advocacy and the current need for the HTT is particularly enlightening example of multiyear swings in facility utilization. The HTT was mostly empty for years and was viewed as being in danger of closure because of low utilization. Had the facility been closed because of shortsighted policies, the nation would have lost a critical hypersonics research facility.

The biggest drawback for these facilities is their general inability to test full-scale articles for long test times. Most of the facilities also have the disadvantage of vitiated air.

Ames Direct-Connect Arc Facility and 16-Inch Shock Tunnel

The Ames Direct-Connect Arc Facility (DCAF) and the Ames 16-Inch Shock Tunnel have been mothballed. Both facilities were used extensively on the NASP Project to establish supersonic combustion and measure boundary layer characteristics as well as the flow chemistry entering the engine. The run time was approximately 10 seconds for the DCAF and 10 milliseconds for the 16-Inch Shock Tunnel. If the concept of supersonic combustion for space access becomes a research project of national choice, then these two facilities should be brought back online and upgraded as appropriate.

Glenn Hypersonic Tunnel Facility

The Glenn Hypersonic Tunnel Facility (HTF) is a blow-down, free-jet WT with a unique non-vitiated air capability. The only other non-vitiated facility is the smaller, 11-Inch Langley Arc-Heated Scramjet Test Facility. HTF has a 42-inch exit diameter nozzle and run times up to 5 minutes.

However, the HTF (like the AEDC facilities) is generally size and speed limited and does not reach Mach numbers greater than 7.0. This limits access to space and hypersonic missile propulsion development. HTF has good user advocacy, but its current very low utilization is endangering the facility's health, given Plum Brook's policy of mothballing any facility when its tests are completed and no near-term tests are scheduled. Thus, HTF is a prime example of a facility in need of shared support, given its unique capabilities and the unresolved research need associated with non-vitiated testing.

Glenn Propulsion Simulation Lab–4

The Glenn Propulsion Simulation Lab (PSL)–4 was included because it can operate up to Mach 6, but this facility is generally size and speed limited and therefore is not often used for hypersonic propulsion testing. We discuss PSL-4 below with the direct-connect propulsion test facilities.

AEDC Aero and Propulsion Test Unit and H-3

The AEDC Aero and Propulsion Test Unit (APTU) and AEDC Arc-Heated H-3 Facility have similar features to the Glenn HTF, are generally limited in size, and do not reach Mach numbers greater than 7.2 (although a funded upgrade for the APTU scheduled for completion in FY2005 will raise its maximum Mach number to 8.0). This limits access to space and hypersonic missile propulsion development.

Army/CUBRC LENS I and LENS II

The Army/CUBRC Large-Energy National Shock (LENS) Tunnels I and II also provide propulsion integration test capabilities in addition to their hypersonic aerodynamic capabilities discussed in the previous section. Together, these facilities offer high-Mach capability and excellent optics testing capabilities. Again, the short run times for LENS I and II (30 milliseconds and 100 milliseconds, respectively) could be a minus for certain applications.

Aero Systems Engineering Channel 9

In addition to its hypersonic aerodynamic capabilities discussed in the previous section, the ASC 20-Inch Channel 9 Hypersonic Wind Tunnel provides some propulsion integration test capabilities needed by the MDA. Channel 9 offers high-Mach capability and is good for research, but it is limited in size and has low advocacy outside MDA.

Veridian 48-Inch and 96-Inch Shock Tubes

Veridian's 48-Inch and 96-Inch Shock Tubes (also discussed under the hypersonic wind tunnel section above) were previously operated by the CALSPAN Corporation. These facilities offer broad and high-Mach capability and excellent optics testing capabilities. Again, possible minuses for these facilities are their short test duration capabilities.

Conclusions and Recommendations for Existing Hypersonic Propulsion Integration Test Facilities

Major challenges remain for hypersonic propulsion integration test facilities, especially in supersonic combustion. Basic physics and chemistry questions linger as well. These challenges demand new approaches, research, updated or modified facilities (perhaps new facilities), and, in general, a change in the way of designing an aircraft or missile.

New propulsion approaches are being explored in updated and modified facilities. Nearly all hypersonic facilities are *essential* to the hypersonics programs, but facility shortcomings are affecting research progress. Issues include scaling, test time duration limitations, and the issue of vitiated test air affecting combustion chemistry. Serious research challenges may require new facilities and approaches for breakthroughs.

Unfortunately, we cannot at present justify new facilities based on the *proven* viability of propulsion concepts, since this viability is still uncertain. Thus, if the nation wants to advance the unknowns in hypersonics, it needs a strategic national vision and investment in facility technology research (to understand what kinds of facilities are needed) and continued propulsion research to explore whether the promise of air-breathing hypersonic propulsion can be made a reality. This will require investments to improve and expand hypersonic facilities to explore whether or not the concepts are viable, preferably informed by facility and propulsion research to enlighten investment decisions in the next five to ten years.

CHAPTER EIGHT

Direct-Connect Propulsion Test Facilities

Here we describe our analysis of the direct-connect propulsion test facilities in light of our analysis of testing needs. These involve the full range of facilities where the air is blown through the engine under study.

Table 8.1 presents an overview of the special capabilities and shortcomings of NASA and DoD facilities. Most of the DoD facilities at AEDC and the NASA propulsion simulation labs at Glenn are capable of both direct-connect propulsion testing and testing in free-jet mode. In free-jet mode, air is blown not only through the engine under study but also around it. Additional technical specifications of these facilities can be found in Table 8.2 and Appendixes F and G (which include the facilities' Web sites).

The special capabilities identified in Table 8.1 include size, engine types (rockets, turbojets, ramjets, and turboshafts), missile-base heating, aerodynamics, aerothermodynamics, PAI, and free-jet expansion of rocket exhaust plumes. The shortcomings listed were few, since the facilities are geared toward either small, medium, or large applications. We did note, however, that the ECRL 2B has only an ambient temperature capability and that the large C1 and C2 cells at AEDC are very expensive for R&D programs.

Table 8.3 presents a summary of the advocacies received from current NASA programs, DoD representatives, and industry representatives for the direct-connect propulsion test facilities.[1]

Advocacy for the Glenn R&D cells and the comparable AEDC cells were generally strong and consistent across the board. The ECRL 2b is primarily a components research laboratory employed by NASA and Army research programs.

Questionnaire responses indicated that AEDC has a larger user base than PSL. General Electric (GE) and Pratt & Whitney conduct significant in-house testing. Engine testing (primarily T&E) for large commercial aircraft and all military aircraft are conducted at AEDC. AEDC is the testing site of choice for all DoD services for which PSL is a backup facility when AEDC cells are unavailable because of high workloads. PSL capabilities are a subset of the total capabilities offered by AEDC but are more affordable (especially for R&D). Thus, engine testing on NASA programs are conducted at PSL (where they are also collocated with research staff).

[1] The advocacy data are illustrative and informative rather than comprehensive and dogmatic. As with the advocacies shown before, we note that such strategic advocacies are enlightening but do not necessarily predict future utilizations.

Table 8.1
Special Capabilities and Shortcomings of NASA and Related AEDC Direct-Connect Propulsion Test Facilities Under Study

		Special Capabilities												Shortcomings	
		Engine Size			Engine Types				Modeling			PAI	Free-Jet Expansion of Rocket Plumes		
Owner	Direct-Connect Propulsion Test Facilities	Small	Medium	Large	Rockets	Turbo-jets	Ram-jets	Turbo-Shaft	Missile-base Heating	Aero-dynamic	Aero-thermo-dynamic			Ambient Temperature Only	Cost for R&D
Glenn	PSL-3		√			√	√								
	PSL-4		√			√	√	√				√			
	ECRL-2B	√				√		√						X	
AEDC	T-1		√			√				√		√			
	T-2		√			√				√		√			
	T-3	√				√	√			√		√	√		
	T-4		√			√				√		√			
	T-5	√				√				√		√			
	T-6	√			√		√		√	√	√		√		
	T-7	√				√				√		√			
	T-11	√				√	√			√					
	T-12	√				√	√	√		√					
	J-1		√			√	√			√		√			
	J-2		√			√	√			√		√			
	C-1			√		√	√			√		√			X
	C-2			√		√				√		√			X

Table 8.2
Glenn and AEDC Direct-Connect Propulsion Test Facility Capabilities

		Test Section Size						
Owner	Test Facilities	Cross-Section (feet, diameter)	Length (feet)	Total Temperature (°R)	Speed Range (Mach)	Pressure Altitude (feet, nominal)	Capacity of Installed Thrust Stand (pounds)	Primary Use[a]
NASA Glenn	PSL-3	24	39	400–1,060	0–3.0	5,000–90,000	Axial: 40,000 Lateral/Vertical: 15,000 (ea)	(2) (3) (9) (15)
	PSL-4	24	39	370–3,200	0–6.0	5,000–90,000	Axial: 50,000 Lateral/Vertical: 15,000/30,000	(2) (3) (9) (15)
	Engine Components Research Lab (ECRL) 2B	6	6	Ambient	0–0.5	Atmospheric to 40,000	2,500 shaft HP	(2) (15)
AEDC	Propulsion Development Test Cell T-1	12.3	35–57	380–1,110	0–3.0	Sea level to 80,000	30,000	(2) (6) (9) (15)
	Propulsion Development Test Cell T-2	12.3	42–50.5	380–1,110	0–3.0	Sea level to 80,000	30,000	(2) (6) (9) (15)
	Propulsion Development Test Cell T-3	12	15	450–1,660	0–4.0	Sea level to 100,000	20,000	(2) (3) (6) (9) (11) (15)
	Propulsion Development Test Cell T-4	12.3	39–47.8	380–1,110	0–3.0	Sea level to 100,000	50,000	(2) (3) (6) (9) (15)
	Propulsion Development Test Cell T-5	7	17	395–660	0–2.0	Sea level to 80,000	2,000	(2) (6) (9) (15)
	Propulsion Development Test Cell T-6	3	18	430–760	0–3.0	Sea level to 90,000	None	(1) (3) (4) (6) (7) (11)
	Propulsion Development Test Cell T-7	7	9	395–1,110	0–3.0	Sea level to 80,000	1,000	(2) (6) (9) (15)
	Propulsion Development Test Cell T-11	10	17	395–860	0–2.5	Sea level to 100,000	25,000	(2) (3) (9) (15)
	Propulsion Development Test Cell T-12	10	20	395–860	0–2.5	Sea level to 100,000	25,000 or 6,000 shaft HP	(2) (3) (9) (15)
	Propulsion Development Test Cell J-1	16	65	395–1,210	0–3.2	Sea level to 80,000	50,000	(2) (3) (6) (9) (15)
	Propulsion Development Test Cell J-2	20	67.3	395–1,110	0–3.0	Sea level to 80,000	50,000	(2) (3) (6) (9) (15)
	Propulsion Development Test Cell C-1	28	50–85	360–1,480	0–3.8	Sea level to 100,000	100,000	(2) (3) (6) (9) (15)

Table 8.2—Continued

Owner	Test Facilities	Test Section Size: Cross-Section (feet, diameter)	Test Section Size: Length (feet)	Total Temperature (°R)	Speed Range (Mach)	Pressure Altitude (feet, nominal)	Capacity of Installed Thrust Stand (pounds)	Primary Use[a]
AEDC (cont.)	Propulsion Development Test Cell C-2	28	50–85	360–1,110	0–3.0	Sea level to 100,000	100,000	(2) (3) (6) (9) (15)
	Propulsion Development Test Cells SL-2/SL-3[b]	24	60	395–810	0–1.25	Sea level	50,000	(2) (3) (9) (15)

SOURCES: NASA Glenn and AEDC. AEDC information is summarized on the "AEDC Test Facilities" statistics sheets, which are online at www.arnold.af.mil/aedc/testhighlights/stats.pdf or www.arnold.af.mil/aedc/valap.htm (last accessed June 2004).

[a]Primary use:

(1) rockets
(2) turbojets
(3) ramjets
(4) missile base heating models
(5) space environmental tests
(6) aerodynamic models
(7) aerothermodynamic models
(8) aeroballistic models
(9) combined aerodynamic inlet and propulsion system tests
(10) impact studies
(11) free-jet expansion of rocket exhaust plumes
(12) ablative materials
(13) ablative and erosive materials
(14) store/stage/separation
(15) turboshaft

[b]Sea level testing cells SL-2 and SL-3 are unique at AEDC and not comparable to NASA facilities. We did not consider them in our analysis.

Table 8.3
Advocacies for NASA and Related AEDC Direct-Connect Propulsion Test Facilities

	NASA at Glenn			AEDC		
Air-Breathing Propulsion	**PSL-3**	**PSL-4**	**ECRL 2b**	**C**	**J**	**T**
Industry						
GE	√	√		√	√	√
P&W	√	√		√	√	√
Williams	√	√			√	√
DoD						
ASC/Air Force[a]	√	√		√	√	√
NAVAIR[a]	√	√		√	√	√
Army			√			
NASA						
RTA/TBCC	√	√				
Other research programs	√	√	√			

SOURCE: Responses to RAND's questionnaire, 2003.
[a]AEDC is the default and preferred choice. PSL is used only as a backup and on rare occasions.

Williams indicated that AEDC cells J1, J2, T4 and the Glenn PSL are comparable facilities. Engine testing for business jets have been conducted at PSL in the past. Williams does not have its own direct-connect propulsion test capability and thus relies on government test facilities.

Allison and Rolls-Royce did not provide survey responses (although Glenn management indicated it continues to receive advocacy and usage from both companies).

Direct-Connect Propulsion Test Facility Health Ratings and Summary Descriptions

Table 8.4 summarizes our analysis of NASA (and related DoD) direct-connect propulsion test facilities. We gave each facility an overall health rating using the levels from Table 3.4 in Chapter Three.

General-Purpose Direct-Connect Propulsion Test Facilities

Glenn Propulsion Simulation Lab Cells 3 and 4

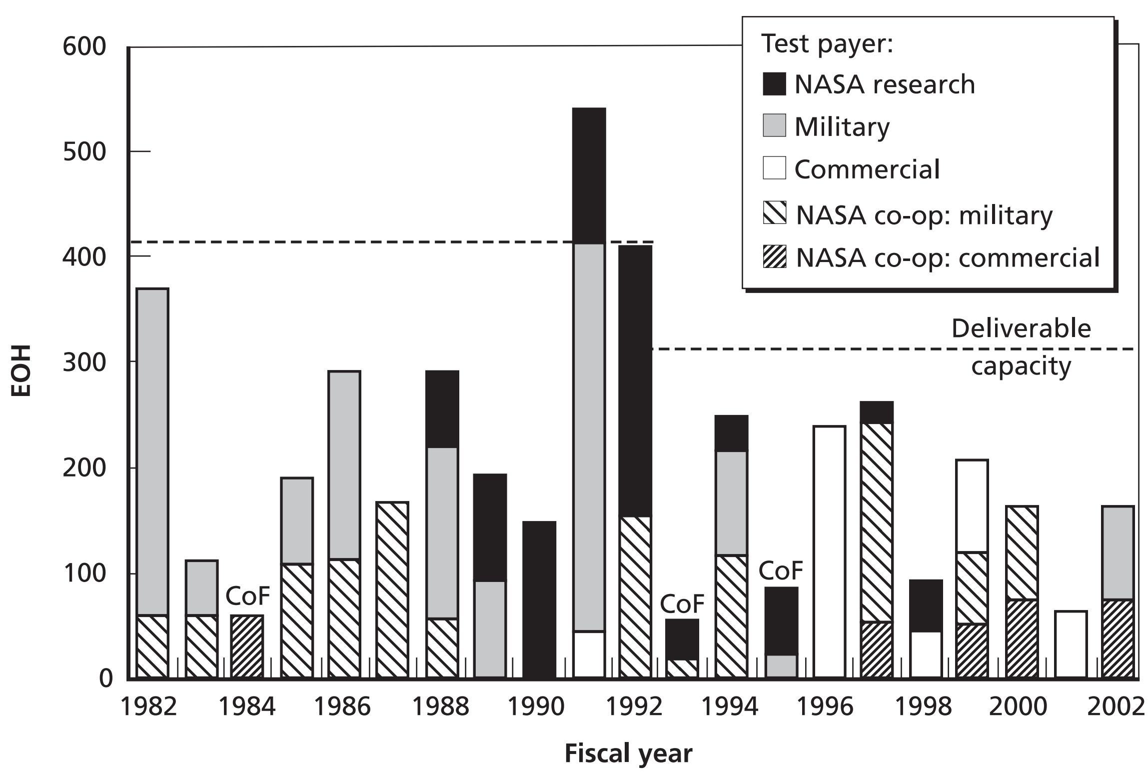
The Glenn Propulsion Simulation Laboratory is NASA's only general-purpose, direct-connect propulsion testing facility capable of testing full-scale engines. It is unique within NASA, but not within the government. PSL cells 3 and 4 are two legs in the same complex tied to central compressed air and exhaust systems. The PSL is used for RDT&E of medium-size engines (e.g., fighter aircraft, business jets) and engine component research.

Figure 8.1 shows the historical engine-on hours utilization of the Glenn PSL from 1992 to 2002, broken down by who paid for the tests. Total EOH during the past two decades has been rather stable overall, albeit with year-to-year variance. NASA pays for much of the testing, even though there is some industry use and the DoD has used the PSL as a backup to AEDC facilities.

Table 8.4
Health Ratings and Summaries of Existing Direct-Connect Propulsion Facilities

Facility	Health	Summary
General-Purpose		
Glenn PSL-3 and PSL-4	Fair	• Used for smaller engines (fighter aircraft, business jets, etc.) and component research • Primary NASA research facilities; also used by industry for component and small engines • Moderate utilization; research could be done at AEDC J1, J2, and T4 • Some industry use • Backup on rare occasions for the DoD
AEDC C, J, and T Cells	Good	• Primary, large T&E capabilities; world's largest • Default and preferred choice for the DoD
Special-Purpose		
Glenn ECRL-2b (small turbines)	Good	• Small turbine engine and components test facility • Used by NASA as well as Army programs (e.g., rotorcraft engines)

Figure 8.1
Historical Utilization at Glenn PSL from 1982 to 2002 by Test Payer

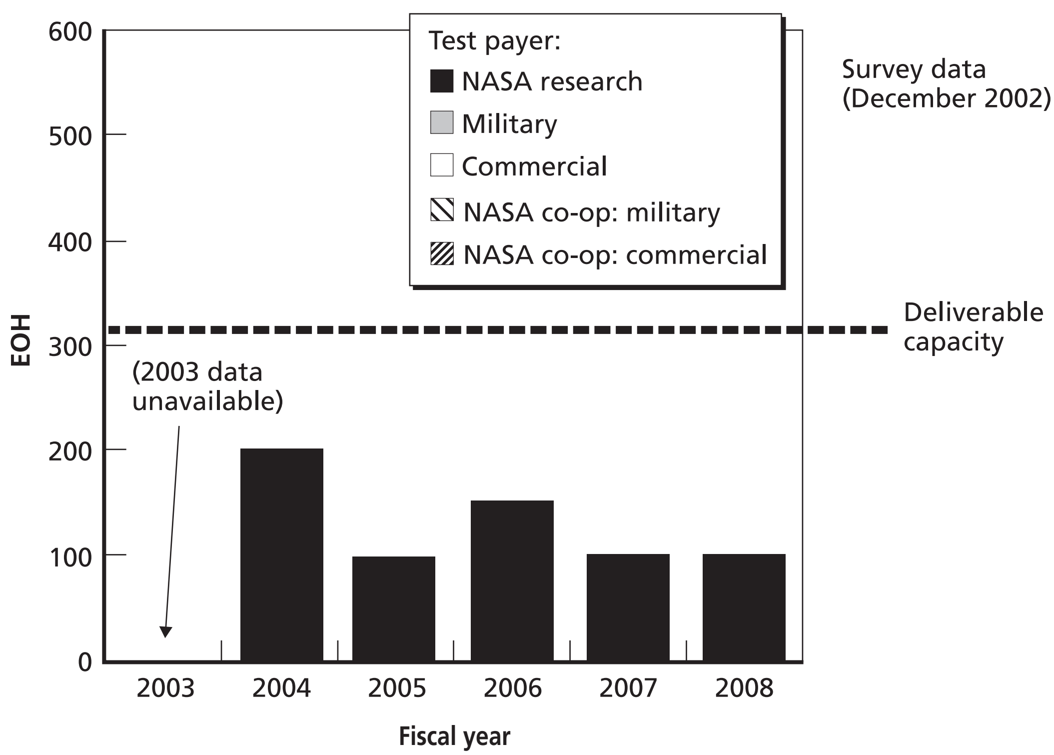


SOURCE: NASA Glenn.
RAND *TR134-8.1*

EOH is the standard measure for test charging by direct-connect propulsion test facilities because those are the hours when the full crew needs to be in place and when the air is on. This is in contrast to WTs that currently record user occupancy hours rather than air-on hours. Unfortunately, EOH does not tell the whole story of facility utilization for the same reason that WTs do not record air-on hours. A large part of the facility time is consumed in engine (or engine component) setup and modification in the facility. For engine testing (and especially engine R&D), this setup can be very time consuming to the point of nearly prohibiting the cyclic insertion and removal of the engine from the facility, given current test section configurations. Additional metrics such as occupancy hours and setup hours specific to the type of research tests would help give a better picture of the usage of these facilities, but such detailed data were not available from Glenn.

Figure 8.2 shows the identifiable future utilization data from our 2002 survey. Interestingly, the only users that were in a position to quantify their future needs were three ongoing NASA research programs—Beamed Power, Revolutionary Turbine Accelerator/Turbine-Based Combined Cycle, and Advanced Aircraft.

Figure 8.2
Projected PSL Engine-On Hours from December 2002 Survey



SOURCE: NASA Glenn.
RAND *TR134-8.2*

Total EOH has been below the deliverable capacity of about 425 hours per year until 1992. Beginning in 1993, Glenn adjusted its deliverable capacity to 338 hours per year to better suit its testing demands. Glenn management has indicated that staff are employed in maintenance and setup operations during engine-off hours. The unavailable UOH data would give us additional information on the actual utilization of the facility test cells. Nevertheless, the fact that EOH has not fallen off in recent years indicates that NASA's propulsion research continues to need the PSL.

PSL was given a "fair" health rating, since the continued shared support from the center (required by the moderate and varying utilization of the PSL) is endangered by NASA's misguided drive to full-cost recovery for test facilities. Glenn management could not specify what the effects of full-cost recovery would be on its current mechanism of obtaining support across programs at the center level to provide shared support to PSL and ensure stable and reasonable test pricing to users.

AEDC Aeropropulsion Systems Test Facility

The ASTF Propulsion Development Test (PDT) cells are the country's primary, large general-purpose T&E capabilities. They include the world's largest direct-connect propulsion test facilities (the C1 and C2 cells). ASTF is critical to meeting DoD mission needs as well as large commercial jet engine testing. However, cost, availability, and location inhibit NASA's use of ASTF.

Small Direct-Connect Propulsion Test Facility

Glenn Engine Components Research Lab Cell 2B

The Glenn ECRL 2B is a special-purpose propulsion test laboratory for research on small turboshaft engines and engine components. ECRL 2B is used by NASA as well as Army programs (e.g., rotorcraft engines) and has some advocacy from industry.

Conclusions and Recommendations for Existing Direct-Connect Propulsion Test Facilities

The PSL cells 3 and 4 are technically comparable (e.g., in size and throughput) to AEDC PDT cells J1, J2, and T4. At first order, this similarity should lead to comparable prices, but it does not. AEDC is much more expensive to users.

PSL requires moderate management attention. Having adjusted its deliverable capacity in 1993 to better meet the relatively flat demand, Glenn (and NASA overall) needs to continue providing the shared support to PSL so vital to its operational health and ensure stable and reasonable testing costs to the nation.

Glenn should continue to stay in touch with Williams, Rolls-Royce, and Allison to understand their evolving needs and perhaps establish a long-term testing arrangement (especially with Williams, which does not have its own testing facilities).

Glenn should record occupancy hours and other relevant data in addition to engine-on data for its direct-connect propulsion test facilities to give a more informed picture of facility use.

PSL is unique within NASA. It satisfies important resident Glenn propulsion programs and thus is a primary facility dependent on NASA's long-term R&D plans. There may be an opportunity for these researchers to utilize AEDC facilities in the future, but key issues for such a plan would be NASA/DoD reliance, availability, and pricing, as well as a solid estimate of the additional costs associated with testing long distance at AEDC and the added expense in time and money of having to pull and reinsert test engines and components from busy cells at AEDC.

APPENDIX A

Glossary

Below are selected key aeronautic terms related to wind tunnel and propulsion test facilities.

Aerodynamics and Wind Tunnels

For further introductory materials regarding wind tunnels, we recommend viewing NASA's "Wind Tunnels at NASA Langley Research Center" fact sheet.[1]

Mach Number

The ratio between the speed of a craft and the speed of sound in the surrounding medium (the atmosphere) is a dimensionless parameter called a Mach number. The speed of air flowing through a wind tunnel is usually expressed in terms of the speed of sound, which is approximately 761 miles per hour at sea level. However, the speed of sound through the atmosphere varies with temperature. Sound travels more slowly through cooler air. Aircraft usually fly at higher Mach numbers in the upper atmosphere, where the air is colder (NASA, 2001; Batchelor, 1967).

Reynolds Number

Reynolds number (Rn) is a nondimensional parameter representing the ratio of the momentum forces to the viscous forces in fluid (gas or liquid) flow. Rn expresses the relationship of the density of the fluid, the velocity, the dimension of an object, and the coefficient of viscosity of the fluid relationship. Osborne Reynolds (1842–1912) demonstrated in his experiments that the fluid flow over a scale model would be the same for the full-scale object if certain flow parameters, or the Rn, were the same in both cases. When the flows around similar objects share the same Reynolds and Mach number parameters, then the topology of the flow for each will be identical (e.g., laminar and turbulent flow distribution, location of separation points, wake structure) and the same aerodynamic coefficients will apply (Batchelor, 1967).

A wind tunnel experiment's results are only strictly applicable to flight conditions with the same Reynolds and Mach numbers, but it is very common to test only with matching Mach number, coming up short of the full-flight Reynold's number. Matching both parameters can be difficult, as it requires changes in the working fluid, such as higher pressure or lower temperature, or a different gas. For example, the Rn of one-quarter-scale

[1] NASA fact sheet, 2001. Online at http://oea.larc.nasa.gov/PAIS/windtunnels.html (last accessed June 2004).

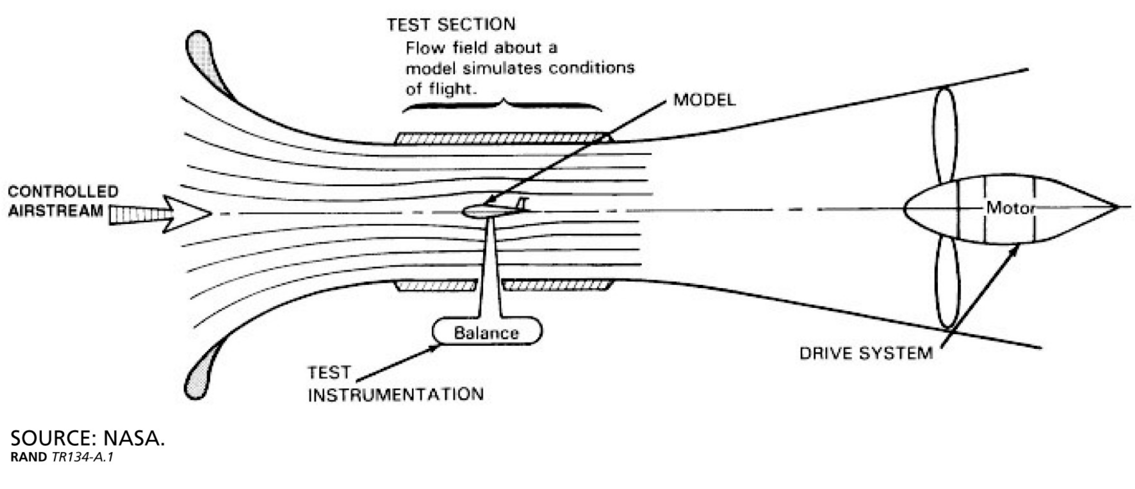
models tested at flight velocities at atmospheric pressure would be too low by a factor of 4. Because the Rn is also proportional to air density, a solution to the problem could be to test 1/4-scale models at a pressure of 4 atmospheres. The Rn would then be the same in the wind tunnel tests and actual full-scale flights.

Experience with similar airframes allows engineers to predict how vehicle aerodynamics will change between the test condition and flight condition, and often such extrapolations will prove adequate (particularly if the underlying flow structure changes slowly with Rn). However, it is not uncommon for a nuance of a newer design to invalidate predictions based on previous experience. Without testing at full-flight Rn, there is always a risk of incorrect estimation (Batchelor, 1967; NASA, 2001b).

Wind Tunnel

A wind tunnel (see Figure A.1) is an enclosed passage through which air is driven by a fan or any appropriate drive system. The heart of the wind tunnel is the test section where a scale model is supported in a carefully controlled airstream that produces a flow of air about the model that duplicates the full-scale aircraft. Appropriate balances and test instrumentation measure the aerodynamic characteristics of the model and the field around it (its flow field). Although the form of a wind tunnel can vary, all wind tunnels have a drive system and a test section and use a model that is supported in an airstream and whose characteristics are measured by test instrumentation. The wind tunnel allows the aerodynamic forces of lift, drag, and side force in reference to the tunnel axis (the axial centerline of the test section) to be measured.[2]

Figure A.1
Wind Tunnel Diagram



SOURCE: NASA.
RAND *TR134-A.1*

[2] See www.centennialofflight.gov/essay/Dictionary/wind_tunnel/DI46.htm (last accessed June 2004).

Facility Conditions

Abandoned Facility

Considered here to be a facility that has no maintenance, no upkeep, parts may be scavenged, etc. An abandoned facility may become nearly worthless after, say, two years.

Mothballed Facility

Considered here to be a facility that has minimal maintenance and could be brought back online (fully functional) in two months or less.

Standby Facility

Considered here to be a facility left in a condition that is periodically operated and could be brought back online (fully functional) for a test in a matter of days. The workforce will remain intact and their skills maintained.

Accounting Terms

Full-Cost Accounting

NASA's *Full Cost Initiative Agencywide Implementation Guide* (1999) defines full cost as involving direct costs, service costs, and general and administrative (G&A) costs. *Direct costs* are costs that can be obviously and/or physically linked to a particular project; *service costs* are costs that cannot be readily or immediately linked to a project but can subsequently be traced to a project; and *G&A costs* are support costs that cannot be linked to any specific project in an economical manner.

APPENDIX B

U.S. Test Facilities

Table B.1
U.S. Subsonic WTs

Name	Test Section	Mach Number	Rn (per ft × 10^6)	Organization	Web Site
National Full-Scale Aerodynamics Complex (NFAC) 80×120-Foot	80H×120W (ft)	0–100 knots	0–1.2	NASA Ames Research Center	windtunnels.arc.nasa.gov/
NFAC 40×80-Foot	39H×79W×80L (ft)	0–300 knots	0–3	NASA Ames Research Center	windtunnels.arc.nasa.gov/
Unitary 12-Foot Pressure Wind Tunnel	11.3H×11.3W×28L (ft)	0.05–0.55	0.1–12	NASA Ames Research Center	windtunnels.arc.nasa.gov/
9×15-Foot Low-Speed Wind Tunnel	9H×15W×28L (ft)	0–0.2	0–1.4	NASA Glenn Research Center	facilities.grc.nasa.gov/9x15/index.html
Icing Research Tunnel (IRT)	6H×9 W×20L (ft)	50–395 mph		NASA Glenn Research Center	facilities.grc.nasa.gov/irt/index.html
14×22-Foot Subsonic Tunnel	14.5H×21.75W×50L (ft)	0–0.3	0–2.1	NASA Langley Research Center	wte.larc.nasa.gov/facilities/aerodynamics/14X22.cfm?field=1&id=2&fac=1
Low-Turbulence Pressure Tunnel (LTPT)	7.5H×3W×7.5L (ft)	0.05–0.5	0.4–15	NASA Langley Research Center	wte.larc.nasa.gov/facilities/aerodynamics/low.cfm?field=3&id=2&fac=1
12-Foot Low-Speed Tunnel	12H×15W (ft)	0–77 ft/sec	0–0.5	NASA Langley Research Center	wte.larc.nasa.gov/facilities/facilities_type.cfm?id=2&fac=4
20-Foot Vertical Spin Tunnel	20 diameter × 25H (ft)	0–85 ft/sec	0–0.15	NASA Langley Research Center	wte.larc.nasa.gov/facilities/flight_dynamics/20foot.cfm?field=7&id=2&fac=1
Subsonic Aerodynamic Research Laboratory (10×7-Foot)	10×7 (ft)	0.2–0.5		Air Force Research Laboratory	www.wrs.afrl.af.mil/infores/facilities/fac_102.htm
Vertical Wind Tunnel	12 diameter (ft)	0–0.14	0–0.91	Air Force Research Laboratory	www.wrs.afrl.af.mil/infores/facilities/fac_101.htm

Table B.1—Continued

Name	Test Section	Mach Number	Rn (per ft × 10^6)	Organization	Web Site
Army Aero-mechanics Lab	7×10 (ft)	0–0.33	0–2.1	Army Aero-mechanics Lab (at NASA Ames Research Center)	www.worthey.net/windtunnels/
8×10-Foot Subsonic Wind Tunnel	8H×10W×14L (ft)	10–275 ft/sec		Naval Surface Warfare Center–Carderock Division	www50.dt.navy.mil/facilities/data/swtdata.html
Low-Speed Wind Tunnel	8H×12W×15L (ft)	0.04–0.36	0.25–2.5	Allied Aerospace (Microcraft)	www.alliedaerospace.com/Wind%20Tunnel%20Testing.htm
20×20-Foot Subsonic Wind Tunnel	20H×20W×45L (ft)	0–215 knots	0–2.3	Boeing	www.boeing.com/assocproducts/techsvcs/boeingtech/bts_aeroe.html
9×9-Foot Subsonic Propulsion Wind Tunnel	9H×9W×19.5L (ft)	0–200 knots		Boeing	www.boeing.com/assocproducts/techsvcs/boeingtech/bts_aerod.html
Boeing Research Aero/Icing Tunnel	4×6 (ft)	0–250 knots		Boeing	www.boeing.com/assocproducts/techsvcs/boeingtech/bts_aerof.html
BTS-Low Speed Aeroacoustic Facility	9×12 (ft) 7×10 (ft)	0.25 0.32		Boeing	www.boeing.com/assocproducts/techsvcs/boeingtech/bts_acoub.html
John J. Harper Low-Speed Wind Tunnel	7×9 (ft)	10–220 ft/sec	0–1.6	Georgia Institute of Technology	www.ae.gatech.edu/research/windtunnel/expaero/jjht.html
Low-Speed Wind Tunnel #1	30×26 (ft)	14–146 ft/sec	0–1	Lockheed Martin	www.worthey.net/windtunnels/
Low-Speed Wind Tunnel #2	16×23 (ft)	29–293 ft/sec	0–2	Lockheed Martin	www.worthey.net/windtunnels/
8×12-Foot	8×12 (ft)	0–293 ft/sec	0–1.7	Lockheed Martin	www.worthey.net/windtunnels/
Wright Brothers Wind Tunnel	7.5 × 10 elliptical × 15L (ft)	0–0.25	0–1.8	Massachusetts Institute of Technology	web.mit.edu/aeroastro/www/labs/WBWT/wbwt_industry_info.doc (download)
7×10-Foot Low-Speed Wind Tunnel	7H×10W×20L (ft)	0–300 mph	1.8	Northrop Grumman	www.is.northropgrumman.com/test/test_capabilities/wind_tunnel/wind_tunnel.html
Langley Full-Scale Tunnel	30H×60W×56L (ft)	13–80 mph	0.73	Old Dominion University	www.lfst.com

Table B.1—Continued

Name	Test Section	Mach Number	Rn (per ft × 10^6)	Organization	Web Site
Oran W. Nicks Low-Speed Wind Tunnel	7H×10W×12L (ft)	0–0.25	0–1.9	Texas A&M	wind.tamu.edu/facility.htm
Large Subsonic Wind Tunnel	8 octagonal × 16L (ft) 10×15×31 (ft) 18 octagonal × 40L (ft)	0–0.9 0–0.45 0–0.26	4.5 2.6 1.6	United Technologies	www.worthey.net/windtunnels/
Acoustic Research Tunnel	5 diameter (ft) 50D(in)×8L(ft)	0–0.65 0–0.35	4.6 4.6	United Technologies	www.worthey.net/windtunnels/
Pilot Wind Tunnel	4×6×8 (ft)	0.12	0.90	United Technologies	www.worthey.net/windtunnels/
Glenn L. Martin Wind Tunnel	7.75H×11.04W (ft)	0–0.3		University of Maryland	www.aero.umd.edu/research/gmwt.html
F. K. Kirsten Wind Tunnel	8H×12W×10L (ft)	0–250 mph	0–1.8	University of Washington	www.uwal.org
Stability Wind Tunnel	6H×6W×24L (ft)	275 ft/sec	0–1.66	Virginia Polytechnic Institute and State University	www.aoe.vt.edu/research/facilities/stab/
Walter H. Beech Memorial Wind Tunnel	7×10 (ft)	5–160 mph	0–1.5	Wichita State University	www.niar.twsu.edu/niar/aerolab/

Table B.2
U.S. Transonic WTs

Name	Test Section	Mach Number	Rn (per ft × 10^6)	Organization	Web Site
Unitary 11-Foot Transonic Wind Tunnel	11H×11W×22L (ft)	0.2–1.5	0.3–9.6	NASA Ames Research Center	windtunnels.arc.nasa.gov/
8×6-Foot Supersonic Wind Tunnel	8H×6W×23.5L (ft)	0.25–2.0	3.6–4.8	NASA Glenn Research Center	facilities.grc.nasa.gov/8x6/index.html
16-Foot Transonic Tunnel (16TT)	15.5 (octagonal) ×22L (ft)	0.2–1.25	1–4	NASA Langley Research Center	wte.larc.nasa.gov/facilities/aerodynamics/16foot.cfm?field =2&id=2&fac=1
National Transonic Facility (NTF)	8.2H×8.2W×25L (ft)	0.1–1.2	4–146	NASA Langley Research Center	wte.larc.nasa.gov/facilities/aerodynamics/national.cfm?field =4&id=2&fac=1
Transonic Dynamics Tunnel (TDT)	16H×16W×17L (ft)	0.1–1.2	0.03 (in air) 0.2–10 (in R-134a)	NASA Langley Research Center	wte.larc.nasa.gov/facilities/aeroelasticity/transonic.cfm?field =14&id=2&fac=1
16-Foot Propulsion Wind Tunnel (16T)	16H×16W×40L (ft)	0.06–1.6	0.1–6.0	Air Force Arnold Engineering Development Center	www.arnold.af.mil/aedc/factsheets/pwt/PWT.pdf
4-Foot Propulsion Wind Tunnel (4T)	4H×4W×12.5L (ft)	0.2–2.0	~2–6	Air Force Arnold Engineering Development Center	www.arnold.af.mil/aedc/factsheets/pwt/PWT.pdf
Channel 10	66H×66W (in)	0–1.15	4.2 at Mach 1	Aero Systems Engineering	www.aerosysengr.com/Aero_Test_Services/ATCapabilities/ Channel_6_and_10/channel_6_and_10.html
Boeing Transonic Wind Tunnel (BTWT)	8×12×14.5 (ft)	0–1.1	0–4	Boeing	www.boeing.com/assocproducts/techsvcs/boeingtech/bts_aerob. html
Veridian Transonic Wind Tunnel	8H×8W×18.75L (ft)	0.2–1.35	0–5 (conventional) 0–12.5 (ejector augmentation)	Veridian	www.veridian.com/offerings/suboffering.asp?offeringID=360& historyIDs=0,227,360

Table B.3
U.S. Supersonic WTs

Name	Test Section	Mach Number	Rn (per ft × 10^6)	Organization	Web Site
Unitary 9×7-Foot Supersonic Wind Tunnel	7H×9W×11L (ft)	1.5–2.55	0.5–5.7	NASA Ames Research Center	windtunnels.arc.nasa.gov/
Abe Silverstein Supersonic Wind Tunnel (10x10-Foot)	10H×10W×40L (ft)	0–0.4 2.0–3.5	0.2–3.5 2.1–3.0	NASA Glenn Research Center	facilities.grc.nasa.gov/10x10/index.html
Unitary Plan Wind Tunnel (UPWT)	4H×4W×7L (ft)	1.5–2.9 2.3–4.6	0.5–6 0.5–11	NASA Langley Research Center	wte.larc.nasa.gov/facilities/aerodynamics/unitary.cfm?field=5&id=2&fac=1
Trisonic Gas-dynamics Facility	2×2 (ft)	0.23–0.8, 1.5, 1.9, 2.3, 3.0	0.5–7	Air Force Research Laboratory	www.wrs.afrl.af.mil/infores/facilities/fac_100.htm
16-Foot Propulsion Wind Tunnel (16S)	16H×16W×40L (ft)	1.5–4.75[a]	0.1–2.6	Air Force Arnold Engineering Development Center	www.arnold.af.mil/aedc/factsheets/pwt/PWT.pdf
Trisonic Wind Tunnel	7H×7W (ft)	0.3–3.5	2–19	Allied Aerospace (GASL)	www.alliedaerospace.com/Wind%20Tunnel%20Testing.htm
Polysonic Wind Tunnel	4H×4W (ft)	0.30–5.05	1–48	Boeing	www.boeing.com/assocproducts/techsvcs/boeingtech/bts_aeroh.html
Lockheed Martin Missile and Fire Control (Dallas) High Speed Wind Tunnel	4H×4W×5L (ft)	0.4–4.8	4–34	Lockheed Martin	www.worthey.net/windtunnels/

[a]The Mach range has been limited to 1.6–2.2. An upgrade to extend the range to 1.5–4.75 is in progress with an initial operating capability scheduled for March 2004.

Table B.4
U.S. Hypersonic WT/PT Facilities

Name	Test Section	Mach Number	Rn (per ft $\times 10^6$)	Organization	Web Site
Hypersonic Tunnel Facility (HTF)	42 diameter (in) 10–14 ft	5, 6, 7		NASA Glenn Research Center	http://facilities.grc.nasa.gov/htf/index.html
8-Foot High Temperature Tunnel (HTT)	8 diameter × 12L (ft)	4, 5, 7	0.3–5.1	NASA Langley Research Center	http://wte.larc.nasa.gov/facilities/hypersonic/8ft.cfm?field=10&id=2&fac=1
Arc-Heated Scramjet Test Facility	4 diameter × 11L (ft)	4.7–8.0	0.04–2.2	NASA Langley Research Center	http://wte.larc.nasa.gov/facilities/hypersonic/arc-heated.cfm?field=11&id=2&fac=1
Combustion-Heated Scramjet Test Facility	42H×30W×96L (in)	3.5–6.0	1.0–6.8	NASA Langley Research Center	http://wte.larc.nasa.gov/facilities/hypersonic/combustion.cfm?field=12&id=2&fac=1
NASA HYPULSE		5–30		NASA; Allied Aerospace (GASL)	www.alliedaerospace.com/Wind%20Tunnel%20Testing.htm
Mach 6, High Rn	12 diameter (in)	6	30	Air Force Research Laboratory	www.wrs.afrl.af.mil/infores/facilities/fac_97.htm
20-Inch Hypersonic Wind Tunnel	20 diameter (in)	12, 14	1	Air Force Research Laboratory	www.wrs.afrl.af.mil/infores/facilities/fac_98.htm
von Karman Gas Dynamics Facility (VKF) Hypersonic Wind Tunnel A	40 (in sq.)	1.5–5.5		Air Force Arnold Engineering Development Center	www.arnold.af.mil/aedc/factsheets/vkf/VKF.pdf
VKF Hypersonic Wind Tunnel B	50 (in)	6, 8		Air Force Arnold Engineering Development Center	www.arnold.af.mil/aedc/factsheets/vkf/VKF.pdf
VKF Hypersonic Wind Tunnel C	25 diameter (in) 50 diameter (in)	4, 6, 10		Air Force Arnold Engineering Development Center	www.arnold.af.mil/aedc/factsheets/vkf/VKF.pdf
Hypervelocity Wind Tunnel 9	5 diameter × 12L (ft)	7, 8, 10, 14, 16.5	0.072 at M14 55.7 at M8	Air Force Arnold Engineering Development Center	www.arnold.af.mil/aedc/tun9ov.htm
Channel 9	20 diameter (in)	7, 11, 14		Aero Systems Engineering	www.aerosysengr.com/Aero_Test_Services/ATCapabilities/Channel_9/channel_9.html
B30 Hypersonic Shock Tunnel (B30 HST)	12-inch diameter nozzle 30-inch nozzle	5–8 8–20		Boeing	www.boeing.com/assocproducts/techsvcs/boeingtech/bts_aerog.html
Large Energy National Shock Tunnel–Leg I (LENS I)	8 diameter × 28L (ft)	8–18	0.001–100	Calspan–University of Buffalo Research Center (CUBRC)	www.cubrc.org/aerospace/index_selectfacility.html
Large Energy National Shock Tunnel–Leg II (LENS II)	8 diameter × 41.7L (ft)	4.5–8	0.05–30	CUBRC	www.cubrc.org/aerospace/index_selectfacility.html

APPENDIX C

Foreign Test Facilities

Table C.1
Foreign Subsonic WTs

Name	Test Section	Mach Number	Rn (per ft × 10^6)	Country	Organization	Web Site
9×9 Low Speed Wind Tunnel	9.1H×9.1W×22.9 L (m)	0–55 m/sec		Canada	National Research Council, Institute for Aerospace Research	iar-ira.nrc-cnrc.gc.ca/aero_6.html
2×3 Wind Tunnel	1.9×2.7×5.2 (m)	0–140 m/sec		Canada	National Research Council, Institute for Aerospace Research	iar-ira.nrc-cnrc.gc.ca/aero_7.html
5m Vertical Wind Tunnel	5 diameter (m) 3×3 (m)	0–28 m/sec		Canada	National Research Council, Institute for Aerospace Research	iar-ira.nrc-cnrc.gc.ca/aero_9b.html
Filton 12×10	12×10×25 (ft)	0.25	1.4	United Kingdom	BAE	www.sata.aero/members/tunnels/9.html
Avro Low-Speed Closed Return Tunnel	2.75×2.23×5.5 (m)	0–70 m/sec		United Kingdom	Flow Science—Goldstein Research Laboratory	www.flow-science.eng.man.ac.uk/avro.htm
Environmental Wind Tunnel	4.57×1.52×9.14 (m)	0–20 m/sec		United Kingdom	Flow Science—Goldstein Research Laboratory	www.flow-science.eng.man.ac.uk/et.htm
5 Metre Low Speed Wind Tunnel	4.2×5.0×6.0 (m)	0.05–0.34	7.6	United Kingdom	QinetiQ	www.sata.aero/members/tunnels/21.html
DA-LSWT	2.1×2.1×4.3 (m)	6–75 m/sec	0.08–1.0	Germany	Airbus Deutschland GmbH	www.aa.washington.edu/sata/members/tunnels/17.html
Icing Wind Tunnel				Italy	Italian Aerospace Research Center (CIRA)	www.cira.it/mezzidiprova/M002_eng.htm
Large, Low-Speed Facility	6.0×6.0×15 (m) 8.0×6.0×20.0 (m) 9.5×9.5×20.0 (m)	0–152 m/sec 0–116 m/sec 0–60 m/sec	6.0 5.3 3.9	The Netherlands	German-Dutch Wind Tunnels (DNW)	www.dnw.aero/facilities/index.htm
Low-Speed Tunnel	3H×2.25W×8.75L (m)	0–80 m/sec	1.4	The Netherlands	DNW	www.dnw.aero/facilities/index.htm
Low-Speed Wind Tunnel Braunsch-weig (NWB)	3.25×2.80 (m)	0–90 m/sec	1.8	Germany	DNW	www.dnw.aero/facilities/index.htm
Cryogenic Wind Tunnel Köln (KKK)	2.4×2.4×5.4 (m)	0–0.38	9.5	Germany	DNW (DLR)	www.dnw.aero/facilities/index.htm
Low-Speed Wind Tunnel LT1	3.6 (diameter) ×8L (m)	0–80 m/sec		Sweden	FOI (Swedish Defence Research Agency)	www.foi.se/english/activities/983971605.html/

Table C.1—Continued

Name	Test Section	Mach Number	Rn (per ft × 10^6)	Country	Organization	Web Site
F1	3.5H×4.5W×11L (m)	0.05–0.36	8	France	ONERA (National Aerospace Studies and Research Office)	www.onera.fr/gmt-en/table.html
F2	1.8H×1.4W×5L (m)	≤100 m/sec	1.1	France	ONERA	www.onera.fr/gmt-en/table.html
S1MA	8(diameter) ×14L (m)	0.05–1		France	ONERA	www.onera.fr/gmt-en/table.html
Large Subsonic Wind Tunnel Emmen	5H×7W (m)	0–68 m/sec	0–4.5	Switzerland	RUAG Aerospace	www.sfaerospace.ch/pdf/LWTE_scrn.pdf
L-1B	2H×3Wx20L (m)	2–50 m/sec		Belgium	Von Karman Institute for Fluid Dynamics	www.vki.ac.be/facilities/index.html
IAI-LSWT	3.66×2.59×6 (m)	0–100 m/sec	6	Israel	Israel Aircraft Industries	www.aa.washington.edu/sata/members/tunnels/35.html
Open-Circuit Low-Speed Wind Tunnel	4.25×2.75 (m)	0–70 m/sec		India	Indian Institute of Science	aero.iisc.ernet.in/facilities/aerodyn_facilities.html
National Wind Tunnel Facility	3×2.25×8.75 (m)	0–80 m/sec	6	India	Indian Institute of Technology Kanpur	www.iitk.ac.in/nwtf/
Low-Speed Wind Tunnel	6.5×5.5 (m)	1–70 m/sec		Japan	National Aerospace Laboratory of Japan	www.nal.go.jp/eng/research/wintec/000.html
Low-Speed Wind Tunnel	3×3×12 (m)	10–100 m/sec		China	Beijing Institute of Aerodynamics	www.bia701.com/html/e_15_fd09_07.htm
T-101	24×14 (elliptical) (m)	5–55 m/sec	3.3	Russia	Central Aerohydrodynamic Institute (TsAGI)	www.tsagi.ru/eng/areas/test_facilities/
T-102	4×2.33 (m)	5–55 m/sec	3.3	Russia	TsAGI	www.tsagi.ru/eng/areas/test_facilities/
T-103	2.33×4 (m)	5–110	7	Russia	TsAGI	www.tsagi.ru/eng/areas/test_facilities/
T-104	7 (diameter) (m)	15–125	8	Russia	TsAGI	www.tsagi.ru/eng/areas/test_facilities/
T-107	2.7 (diameter) (m)	0.15–0.90	14.5	Russia	TsAGI	www.tsagi.ru/eng/areas/test_facilities/

Table C.2
Foreign Transonic WTs

Name	Test Section	Mach Number	Rn (per ft × 10^6)	Country	Organization	Web Site
Transonic Wind Tunnel	2.74×2.44 (m)	0.2–1.4		United Kingdom	Aircraft Research Association	www.ara.co.uk/facilities%20frames%20page.htm
PT-1 Transonic Wind Tunnel		0.1–1.1, 1.4		Italy	CIRA	www.cira.it/mezzidiprova/M003_eng.htm
High-Speed Tunnel	2.0×1.8 (m)	0.1–1.35	9	The Netherlands	DNW NLR	www.dnw.aero/facilities/index.htm
European Transonic Windtunnel (ETW)	2.0H×2.4W×9.0L (m)	0.15–1.35	0–50 (full-span aircraft model) 0–85 (wall-mounted semi-span model)	Germany (European Union)	European Transonic Windtunnel GmbH	www.etw.de/windtunnel/windtunnel.htm
Transonic Wind Tunnel	2H×2W (m)	0.4–1.4		Japan	National Aerospace Laboratory of Japan	www.nal.go.jp/eng/research/wintec/000.html
T-106	2.48 diameter round (m)	0.15–1.1	35	Russia	TsAGI	www.tsagi.com/areas/test_facilities/

Table C.3
Foreign Supersonic WTs

Name	Test Section	Mach Number	Rn (per ft $\times 10^6$)	Country	Organization	Web Site
Trisonic Blowdown Wind Tunnel	1.5×1.5 (m) or 0.38×1.5 (m)	0.1–0.75 0.7–1.4 1.1–4.25	80 160	Canada	National Research Council, Institute for Aerospace Research	iar-ira.nrc-cnrc.gc.ca/aero_8.html
Supersonic Wind Tunnel	0.69×0.76 (m)	1.4–3.0	20 (at Mach 1.4)	United Kingdom	Aircraft Research Association	www.ara.co.uk/facilities%20frames%20page.htm
Transonic Wind Tunnel Göttingen	1H×1W (m)	0.3–0.9 0.5–1.2 1.3–2.2	1.8	Germany	DNW DLR	www.dnw.aero/facilities/index.htm
Supersonic Tunnel	1.2H×1.2W (m)	1.2–4.0	15	The Netherlands	DNW NLR	www.dnw.aero/facilities/index.htm
High-Speed Wind Tunnel T1500	1.5H×1.5W×4.0L (m)	0.2–1.25 0.2–0.8, 1.3–2.0	0–80	Sweden	FOI	www.foi.se/english/activities/983966301.html
S4	0.92×0.90 (m) 0.92×1.15 (m)	0.5–2.0	0–13	Sweden	FOI	www.foi.se/english/activities/983970586.html
S2MA	1.77H×1.75W (m) (transonic) 1.935H×1.75W (m) (supersonic)	0.1–3.1	5.4 (transonic) 4.0 (supersonic)	France	ONERA	www.onera.fr/gmt-en/table.html
S3MA	0.76×0.8 (m)	0.1–5.5		France	ONERA	www.onera.fr/gmt-en/table.html
Trisonic Wind Tunnel	4H×4W×5L (ft)	0.5–2.0 1.6–5.0	38	Israel	Israel Aircraft Industries	www.aa.washington.edu/sata/members/tunnels/35.html
Supersonic Wind Tunnel	1H×1W (m)	1.4–4.0		Japan	National Aerospace Laboratory of Japan	www.nal.go.jp/eng/research/wintec/000.html
Trisonic Wind Tunnel	0.6H×0.6W×1.575L (m)	0.4–4.5		China	Beijing Institute of Aerodynamics	www.bia701.com/html/e_17_fd06_02.htm
T-108	1×1 (m)	0.2–1.7	11–20	Russia	TsAGI	www.tsagi.com/areas/test_facilities/
T-109	2.25×2.25 (m)	0.4–4.0	60	Russia	TsAGI	www.tsagi.com/areas/test_facilities/
T-112	0.6×0.6 (m)	0.6–1.8	15	Russia	TsAGI	www.tsagi.com/areas/test_facilities/
T-114	0.6×0.6 (m)	0.3–4.0	20	Russia	TsAGI	www.tsagi.com/areas/test_facilities/
T-128	2.75H×2.75W (m)	0.15–1.7	41	Russia	TsAGI	www.tsagi.com/areas/test_facilities/
T-33	0.8(diameter) (m)	3.0...5.0	70	Russia	TsAGI	www.tsagi.com/areas/test_facilities/
TPD	4.0(diameter) (m)	0.3–4.0	60	Russia	TsAGI	www.tsagi.com/areas/test_facilities/

Table C.4
Foreign Hypersonic WT/PT Facilities

Name	Test Section	Mach Number	Rn (per ft $\times 10^6$)	Country	Organization	Web Site
Hypersonic Wind Tunnel (HWT) 1 of 2	0.3×0.4 (m)	4.0–5.0	40–60	United Kingdom	Aircraft Research Association	www.ara.co.uk/facilities%20frames%20page.htm
HWT 2 of 2	0.3 diameter (m)	6.0 7.0 8.0	70 50 30	United Kingdom	Aircraft Research Association	www.ara.co.uk/facilities%20frames%20page.htm
SCIOROCCO Plasma Wind Tunnel	5 diameter × 9.6H (m)			Italy	CIRA	www.cira.it/mezzidiprova/M001_eng.htm
Rohrwindkanal Göttingen (RWG)	0.5H×0.5W (m) 0.5 diameter (m)	3, 4 5, 6, 6.8	3.5 2.2	Germany	DNW DLR	www.dnw.aero/facilities/index.htm
HYP500	500 diameter (mm)	4 7.15		Sweden	FOI	www.foi.se/english/activities/983971979.html
S4MA	0.68 diameter (m) 1 diameter (m) 1 diameter (m)	6.4 10 12	1.7 0.9 0.35	France	ONERA	www.onera.fr/gmt-en/table.html
F4	670 diameter (mm) 670 diameter (mm) 430 diameter (mm) 930 diameter (mm)	8–17 7–13 6–11 9–21	2 3 5 1	France	ONERA	www.onera.fr/gmt-en/table.html
Hypersonic Wind Tunnel	1.27 diameter (m)			Japan	National Aerospace Laboratory of Japan	www.nal.go.jp/eng/research/wintec/000.html
Hypersonic Wind Tunnel	0.5 (m)	5–8, 10–12		China	Beijing Institute of Aerodynamics	www.bia701.com/html/e_18_f500_04.htm
T-113	0.6×0.6 (m)	1.8–6.0	43	Russia	TsAGI	www.tsagi.com/areas/test_facilities/
T-116	1×1 (m)	1.8–10	47	Russia	TsAGI	www.tsagi.com/areas/test_facilities/
T-117	1 diameter (m)	10–18	4	Russia	TsAGI	www.tsagi.com/areas/test_facilities/
IO-2	0.2 (m) 0.9 (m)	16.3–17.9 10–22	40	Russia	TsAGI	www.tsagi.com/areas/test_facilities/
ST-1	0.3 (m) or 0.5 (m)	5–10	5.3 at Mach 6	Russia	TsAGI	www.tsagi.com/areas/test_facilities/
VAT-3	1 (m)	12–18 12–20	0.03–1.5	Russia	TsAGI	www.tsagi.com/areas/test_facilities/
T-131	1.2 diameter × 2.0L (m)	5–7	10	Russia	TsAGI	www.tsagi.com/areas/test_facilities/
T-313	0.6H×0.6W (m)	1.8–6.0	60	Russia	Institute of Theoretical and Applied Mechanics	

Table C.4—Continued

Name	Test Section	Mach Number	Rn (per ft $\times 10^6$)	Country	Organization	Web Site
UT-302	0.3 diameter (m)	5–15	10	Russia	Institute of Theoretical and Applied Mechanics	
AT-303	0.3H×0.3W (m) 0.6H×0.6W (m)	10–20	100	Russia	Institute of Theoretical and Applied Mechanics	

APPENDIX D
Questionnaires

To gather necessary baseline information, members of the RAND Corporation visited facilities and organizations across the country and overseas, not only to assess capabilities but also to identify programs and research efforts that are likely to require such facilities in the future. RAND used an interview protocol consisting of an initial list of questions to support the gathering of data and information for the study.

Subsequent to this protocol, RAND requested user community representatives in December 2002 to complete a spreadsheet indicating anticipated user occupancy hours (UOH) for wind tunnels and engine-on hours (EOH) for propulsion test facilities. Additional sets of questions were sent in March and April of 2003 to aeronautic design experts to explore deeper questions regarding user needs, aerodynamic issues, and facility issues.

The questions used in these queries are included below.

Interview Protocol Questions

Please generate answers to the following questions as a way of collecting the type of information that will inform our analysis. Please include any official program test documentation that you might deem appropriate (e.g., Integrated Test Plans) with your response. The following stepwise approach may be helpful in generating your answers:

Step 1: Provide detailed information on current programs.
Step 2: Provide detailed information on possible "block upgrades" to current programs, with as much detailed information as possible.
Step 3: Provide as much detailed information as possible on future programs and base the estimate of testing hours at the appropriate level of granularity (category, subcategory) using test requirements of past programs as the baseline.

(a) What aerospace programs or areas (including research, development, and operation) should need the use of wind tunnels or propulsion test facilities in the next 10–25 years? What other programs are you aware of?

- Description of program
- Program stakeholders?
- Relationship to:
  - –Higher-level planning guidance (e.g., national strategy, aeronautic capabilities planning documents)?
  - –Other programs?
- Probability of execution (*definite*, *likely*, *uncertain*)
- Supporting milestones (planned? budgeted?)
- Please provide detailed information on programs or potential future needs with respect to schedule, amount of testing hours by category (rough estimates or range of estimates by sub-, trans-, super-, and hypersonic), subcategory (specific experimental conditions), and time frame, including any of the following that are pertinent:
  - –Type of testing: research, development, or validation/test and evaluation (T&E)
  - –Critical considerations (e.g., cost, availability, lead time in scheduling, scheduling confidence, speed of acquiring data, analysis support)

Interview Protocol Questions—Continued

–Subsonic, transonic, supersonic, hypersonic, propulsion test, propulsion integration
–Mach number (range)
–Critical associated needs (e.g., instrumentation, computational fluid dynamics [CFD], model building, sensors)
–Reynolds number (range)
–Reynolds number per foot for facility
–Pressure effects
–Cryogenics effects
–Tunnel size (cross-sectional area, height, width, length of test section)
–Model characteristics
–Scale of model (lowest acceptable)
–Physical dimensions of model (smallest acceptable)
–Model fabrication technology advances needs
–Data collection of key testing parameters and related instrumentation requirements
–Anticipated instrumentation technology improvements
–Flow characteristics
–Steady-state flow quality (acceptable turbulence levels in the tunnel), dynamic flow, aeroelastics (flutter, buffeting, etc.), spin control (normal and recovery)
–Acoustic characteristics
–Propulsion testing needs
–Productivity needs
–Vitiated/non-vitiated flow needs
–Dynamics testing needs
–Temperature needs
–Relationship to flight test and CFD.

Other important aspects not listed above:

- To what extent do you foresee computational fluid dynamics satisfying your research and development needs? How do you utilize CFD with other test capabilities (e.g., do you integrate CFD and simulations to direct when and where you need to conduct ground or flight tests)?
- Do you find difficulties in relying on different facilities as a result of facility owner prioritization processes? Are you satisfied with the prioritization process? What changes, if any, would you prefer? What effect (e.g., meeting mission, cost, schedule, deadlines) do such uncertainties have on your program?
- How does Technology Readiness Level (TRL) or technology maturity (research, development, or acquisition) affect the type of needs? Is there more flexibility at earlier levels?

(b) What advantages do the facilities you use offer? What disadvantages?

(c) Are there any proprietary data, ITAR (International Traffic in Arms Regulations), or other data protection concerns or issues that need to be addressed by the T&E facilities? Do NASA or DoD facilities meet those needs?

(d) From one view, each class of test facility has instantiations that have different scale and capability aspects (e.g., in a flight analogy, there are Boeing 747s, small business jets, and Piper personal planes, each with different capabilities and costs). Can you explain the effect on your program if you did not have such a range of options to choose from? Can you quantify those costs?

(e) For recent large programs (e.g., F15, F16, F22, JSF, C5, 777, 767, Space Shuttle, National Aerospace Plane), can you provide a facility need and utilization profile that shows the types of facilities needed, overall schedule (including time, facility, and specific reason why that facility was chosen), the magnitude of use across those facilities, and explanation of whether a fewer number of facilities could have met your needs? What would have been the cost and schedule effects if fewer facilities were available? Were there facilities or types of capabilities that you needed but were unable to obtain for any reason (e.g., did not exist; not technically feasible; not able to obtain time at the facility; unable to afford the facility)? How did you determine the level of acceptable risk in not performing more tests or in selecting alternate test methods? When the program was originally conceived and cost estimated, how did you forecast your testing needs?

(f) What kind of general database or records (if any) do you have that describing historical needs and usage?

Hypersonics
(g) What concepts for hypersonics programs are envisioned for the next 10–25 years? What is the probability that one or more of those programs will come through? Do you foresee the commercial sector trailing military and space sectors in the utilization of hypersonics technology? What level and types of hypersonic facilities do you foresee the nation needing in the next 10–20 years? What levels of utilization might those facilities see if a large hypersonic development and acquisition program arises? What would the effect be on hypersonics if we lost the remaining facilities (through either mothballing and loss of technical workforce or having to build new facilities)? Are new hypersonic ground test facilities needed (what type, when, cost estimates, etc.)?

Quantitative Survey of Anticipated Facility Use Hours

The quantitative survey conducted in December 2002 asked user community representatives to complete the spreadsheet shown in the following table (next page) for each type of testing they anticipate needing in the future. We also asked the users to describe the pros and cons of the facilities they are familiar with and to describe any future needs that cannot be met with existing facilities.

Anticipated Testing Spreadsheet Used in the December 2002 Queries

Projected Wind Tunnel Needs (Test Hours)
Preliminary Organization Input

Discipline

Name	
Organization code	
Phone	
Email	

Subsonic Wind Tunnels (Mach range 0–0.6 and ≥ 6 ft test section)
Test Description (e.g., force and moment testing; spin; icing; flutter; dynamic control, store separation)

			Estimated/Projected Test Hours in 100s								
Program	**Facility Requirements**	**Specific Tunnel Required (if known)**	**FY03**	**FY04**	**FY05**	**FY06–07**	**FY08–09**	**FY10–14**	**FY15–19**	**FY20–24**	**FY25–29**
		Totals	0	0	0	0	0	0	0	0	0

Transonic Wind Tunnels (Mach range 0.6–1.5 and ≥ 4 ft test section)
Test Description (e.g., force and moment testing; spin; icing; flutter; dynamic control, store separation)

			Estimated/Projected Test Hours in 100s								
Program	**Facility Requirements**	**Specific Tunnel Required (if known)**	**FY03**	**FY04**	**FY05**	**FY06–07**	**FY08–09**	**FY10–14**	**FY15–19**	**FY20–24**	**FY25–29**
		Totals	0	0	0	0	0	0	0	0	0

Anticipated Testing Spreadsheet Used in the December 2002 Queries—Continued

Supersonic Wind Tunnels (Mach range 1.5–5.0 and ≥ 2 ft test section) Test Description (e.g., force and moment testing; spin; icing; flutter; dynamic control, store separation)											
			Estimated/Projected Test Hours in 100s								
Program	**Facility Requirements**	**Specific Tunnel Required (if known)**	**FY03**	**FY04**	**FY05**	**FY06–07**	**FY08–09**	**FY10–14**	**FY15–19**	**FY20–24**	**FY25–29**
		Totals	0	0	0	0	0	0	0	0	0

Hypersonic Wind Tunnels (Mach range > 5.0 and ≥ 1 ft test section) Test Description (e.g., force and moment testing; spin; icing; flutter; dynamic control, store separation)											
			Estimated/Projected Test Hours in 100s								
Program	**Facility Requirements**	**Specific Tunnel Required (if known)**	**FY03**	**FY04**	**FY05**	**FY06–07**	**FY08–09**	**FY10–14**	**FY15–19**	**FY20–24**	**FY25–29**
		Totals	0	0	0	0	0	0	0	0	0

Air-Breathing Propulsion Test Description (e.g., force and moment testing; spin; icing; flutter; dynamic control, store separation)											
			Estimated/Projected Test Hours in 100s								
Program	**Facility Requirements**	**Specific Tunnel Required (if known)**	**FY03**	**FY04**	**FY05**	**FY06–07**	**FY08–09**	**FY10–14**	**FY15–19**	**FY20–24**	**FY25–29**
		Totals	0	0	0	0	0	0	0	0	0

Caveats

Questions on Facility Needs and Capabilities

These are the questions sent to representatives of the design community in March and April of 2003.

Subsonic Wind Tunnel Questions

(1) For each vehicle, aircraft, missile, etc., class or type that you are now, or expect to be, involved with, what subsonic tunnels do you (or will you) mainly rely on for your technology- and product-development and testing needs?

- NASA?
- DoD?
- Non-U.S. (Canadian, European, other)?
- Private?
- University?

(2) Are there alternatives and/or backups to these primary facilities available that would allow you to fulfill your testing needs if any of the NASA and DoD (and other) tunnels were not available to you? If so:

- What are they?
- What technical risk factors would be involved?
- What cost and scheduling risks might having to use these alternatives entail?

(3) What facility/testing capability voids exist today that would/might limit your ability to incorporate some of the advanced technology concepts that are being proposed such as advanced flow (separation) control concepts, laminar flow control (passive and active), noise reduction concepts, vehicle geometry simplification concepts, morphing, etc.?

- What new facilities would be necessary to permit incorporation of these advanced technologies into viable new products?
- What thoughts do you have regarding the economic benefits versus costs of such new facilities?

(4) For each vehicle/aircraft class or type that you are now or expect to be involved with, what are representative *flight* Reynolds numbers (based on wing MAC or other) at important/critical subsonic low-speed conditions (e.g., takeoff, landing)?

- What are the corresponding Mach numbers?
- What Reynolds numbers are you able to attain with sensibly sized models in the various subsonic wind tunnels that you currently utilize, or plan to utilize?
- What Reynolds numbers do you need/require in order to effectively manage development risk, i.e., preclude significant surprises in flight with existing technologies? With new technologies?
- Do you consider the use of semi-span models as an effective means of increasing attainable wind tunnel test Reynolds numbers for your important/critical subsonic low speed testing needs?

(5) With existing air vehicle aerodynamic technologies, how do wind tunnel flow quality (free-stream turbulence and noise levels, flow angularity, etc.) characteristics influence your determination of what is an acceptable or nonacceptable test facility?

- For general aerodynamic configuration development, especially for smaller vehicles that may have some run/extent of laminar flow in flight?
- For noise reduction concept development studies?
- What tunnels do you use when excellent tunnel flow quality is necessary?
- Do you think the United States is lacking in wind tunnels with the flow quality needed for some applications? If so, what would you suggest for new facilities? What do you think the technical versus economic arguments would be for such facility developments?

(6) How do you balance flow quality requirements versus Reynolds number requirements if you can't get both?

- For general aerodynamic configuration development?
- For noise reduction concept development?
- If you have to sacrifice Reynolds numbers for flow quality in noise reduction studies, is that acceptable to you?

(7) When is having both the necessary flow quality *and* Reynolds number capability an enabling requirement?

- What potentially valuable new technology concepts are having their development and implementation held back by the lack of adequate test facilities that can provide the needed flow quality, Reynolds numbers, etc.?

(8) Is the representative modeling of jet engine (inlet and exhaust) characteristics and/or propeller effects at low speeds in the wind tunnel an important or critical element in your vehicle development efforts?

- If so, which subsonic tunnels have unique/essential capabilities in this regard?
- Which ones are not really useable/reliable in this regard?
- Do you encounter situations where you have to trade Reynolds numbers, flow quality, etc., capabilities in order to simulate power effects? Or vice versa? What development risks does this impose? Any examples of where this has led to "problems"?

- What advanced technology implementations are being curtailed by engine and/or propeller simulation shortfalls?
- What new capabilities (wind tunnel and engine/propeller simulations) do you need to efficiently and effectively develop any potentially promising new concepts/technologies? Any ideas on how these new capabilities could be achieved technically?
- Does the simulation of heat transfer effects (other than for ice accretion effects) ever enter into your choice of acceptable/adequate subsonic wind tunnels?
- Is the inability to simulate/determine heat transfer effects ever a limitation or risk to you?

(9) Considering the numerous "novel" new flow control (e.g., separation onset and progression) concepts under "development," are existing wind tunnel capabilities in the United States adequate to enable the effective and low-risk development and incorporation of these concepts into a range of air vehicle types?

- If not, for which class(es) of vehicles do serious shortcomings exist? What are these deficiencies?
- Is scaling the efficiency of such devices possible, or do you need facilities where full-scale designs can be tested at flight Reynolds numbers with the necessary tunnel flow quality?
- Do you feel that the development of any new subsonic facilities to enable the effective and low-risk development and incorporation of these technologies would be economically justified? Why?

(10) Answer questions in (9) but with regard to the effective and low-risk incorporation of laminar flow control technology, either active or passive, for a range of air vehicle classes.

(11) Is the representative modeling of steady and/or unsteady ground effects in subsonic wind tunnel testing critical to the success of your designs?

- If so, which wind tunnels have the required capabilities (such as moving ground belt)?
- Do such facilities also have adequate Reynolds number and other required/needed capabilities? If not, what compromises/risks are taken to get the ground effects data? How does this impact development risk?
- Are additional capabilities required in this area for the incorporation of any promising new technologies?

(12) What other unsteady flow phenomena (other than flow separation) need to be addressed in subsonic wind tunnel testing of existing and new technologies?

- What capabilities/facilities are needed/required to satisfactorily address flutter, spin characteristics, store and stage separation characteristics, etc., for your product line?
- Are there any documented cases where existing facilities have yielded results not representative of flight? If so, could you give us examples?

(13) How have current state-of-the-art computational fluid dynamics capabilities (e.g., Reynolds Averaged Navier Stokes [RANS] with state-of-the-art turbulence models) allowed you to reduce the amount of subsonic wind tunnel test time needed for the development of the low-speed configuration (e.g., takeoff and landing geometries) of the vehicles you develop and build?

- A feel for about how much?
- What kind of testing has it reduced the need for?
- Can you do some effective screening of concepts prior to testing?
- Does the (generally accepted) inability of current RANS technology to reliably predict flight separation onset and progression characteristics effectively minimize the amount of subsonic wind tunnel testing that you can replace with CFD?
- Do you feel you have adequate access to the latest and best CFD capabilities developed by NASA? DoD (where applicable)?
- Are current CFD limitations (in conjunction with facility limitations) an important obstacle standing in the way of the effective implementation of (separation) flow control, laminar flow control, and other promising new technology concepts? Why?
- What do you think is needed before CFD will permit a significant reduction in the amount of subsonic low speed wind tunnel testing needed for vehicle development?
- Do you believe that emerging large-eddy simulation (LES) or detached-eddy simulation (DES) technologies will eventually allow you to make meaningful reductions in the amount of subsonic wind tunnel testing you need, for either technology- or product-development efforts? Or, do you believe the direct numerical simulation (DNS) will be needed before you can make any further significant reductions in the amount of subsonic wind tunnel testing required?
- What areas, or types of testing, do you believe LES, DES, and/or DNS would allow significant reductions in the amount of subsonic wind tunnel testing required? Any estimates on how long it might be before any of these new technologies are ready and available?
- How would you prioritize needed CFD technology developments versus building any new subsonic tunnels? Or making improvements to existing ones?

(14) Is the NASA Glenn Icing Research Tunnel (IRT) an important/required facility for your vehicle developments?

- If so, would you have problems in going elsewhere (e.g., such as the new CIRA icing tunnel in Italy, private/industry icing tunnels in the United States) if the IRT were not available?
- How do you use icing tunnels such as the IRT in your vehicles development programs? To define the most critical ice shapes? Or for the development and/or validation of your ice protection system?
- How important do you believe improvements to the IRT would be to permit testing of supercooled large droplet (SLD) conditions? For your vehicles?

(15) Do you make a concerted effort to thoroughly document the lessons learned (often the hard way) regarding subsonic (and other) wind tunnel test successes and failures that guide new engineers in selecting appropriate test facilities for current issues/problems associated with either existing or new technology implementations? Are these continually updated? Typically, what form are these in?

Transonic Wind Tunnel Questions

(1) For each vehicle, aircraft, missile, etc., class or type that you are now, or expect to be, involved with, what transonic tunnels do you (or will you) mainly rely on for your technology- and product-development and testing needs?
- NASA?
- DoD?
- Non-U.S. (Canadian, European, other)?
- Private?
- University?

(2) Are there alternatives and/or viable backups to these primary facilities available that would allow you to fulfill your testing needs if any of the NASA and DoD (and other) tunnels were not available to you? If so:
- What are they?
- What technical risk factors would be involved?
- What cost and scheduling risks might having to use these alternatives entail?

(3) What facility/testing capability voids exist today that would/might limit your ability to incorporate some of the advanced technology concepts that are being proposed such as advanced flow (separation) control concepts, laminar flow control (passive and active), vehicle geometry simplification concepts, morphing, etc.?
- What new facilities would be necessary to permit incorporation of these advanced technologies into viable new products?
- What thoughts do you have regarding the economic benefits versus costs of such new facilities?

(4) For each vehicle/aircraft class or type that you are now or expect to be involved with, what are representative *flight* Reynolds numbers (based on wing MAC or other) at important/critical transonic conditions?
- What are the corresponding Mach numbers?
- What Reynolds numbers are you able to attain with sensibly sized models in the various transonic wind tunnels that you currently utilize, or plan to utilize?
- What Reynolds numbers do you need/require in order to effectively manage development risk, i.e., preclude significant surprises in flight with existing technologies? With new technologies?
- Do you consider the use of semi-span models as an effective means of increasing attainable wind tunnel test Reynolds numbers for your important/critical transonic testing needs?

(5) With existing air vehicle aerodynamic technologies, how do wind tunnel flow quality (free-stream turbulence and noise levels, flow angularity, etc.) characteristics influence your determination of what is an acceptable or nonacceptable test facility?
- For general aerodynamic configuration development, especially for smaller vehicles that may have some run/extent of laminar flow in flight?
- What tunnels do you use when excellent tunnel flow quality is necessary?
- Do you think the United States is lacking in wind tunnels with the flow quality needed for some applications? If so, what would you suggest for new facilities? What do you think the technical versus economic arguments would be for such facility developments?

(6) How do you balance flow quality requirements versus Reynolds number requirements if you can't get both?
- For general aerodynamic configuration development?
- Other?

(7) When is having both the necessary flow quality *and* Reynolds number capability an enabling requirement?
- What potentially valuable new technology concepts are having their development and implementation held back by the lack of adequate test facilities that can provide the needed flow quality, Reynolds numbers, etc.?

(8) Is the representative modeling of jet engine (inlet and exhaust) characteristics and/or propeller effects at transonic conditions in the wind tunnel an important or critical element in your vehicle development efforts?
- If so, which transonic tunnels have unique/essential capabilities in this regard?
- Which ones are not really useable/reliable in this regard?
- Do you encounter situations where you have to trade Reynolds numbers, flow quality, etc., capabilities in order to simulate power effects? Or vice versa? What development risks does this impose? Any examples of where this has led to "problems"?
- What advanced technology implementations are being curtailed by engine and/or propeller simulation shortfalls?
- What new capabilities (wind tunnel and engine/propeller simulations) do you need to efficiently and

effectively develop any potentially promising new concepts/technologies? Any ideas on how these new capabilities could be achieved technically?
- Does the simulation of heat transfer effects ever enter into your choice of acceptable/adequate transonic wind tunnels?
- Is the inability to simulate/determine heat transfer effects ever a limitation or risk to you?

(9) Considering the numerous "novel" new flow control (e.g., separation onset and progression) concepts under "development," are existing wind tunnel capabilities in the United States adequate to enable the effective and low-risk development and incorporation of these concepts into a range of air vehicle types?
- If not, for which class(es) of vehicles do serious shortcomings exist? What are these deficiencies?
- Is scaling the efficiency of such devices possible, or do you need facilities where full-scale designs can be tested at flight Reynolds numbers with the necessary tunnel flow quality?
- Do you feel that the development of any new transonic facilities to enable the effective and low-risk development and incorporation of these technologies would be economically justified? Why?

(10) Answer questions in (9) but with regard to the effective and low-risk incorporation of laminar flow control technology, either active or passive, for a range of air vehicle classes.

(11) What unsteady flow phenomena (other than flow separation) need to be addressed in transonic wind tunnel testing of existing and new technologies?
- What capabilities/facilities are needed/required to satisfactorily address flutter, store and stage separation characteristics, etc., for your product line?
- Are there any documented cases where existing facilities have yielded results not representative of flight? If so, could you give us examples?

(12) How have current state-of-the-art computational flight dynamics capabilities (e.g., Reynolds Averaged Navier Stokes [RANS] with state-of-the-art turbulence models) allowed you to reduce the amount of transonic wind tunnel test time needed for the development of the transonic configuration of the vehicles you develop and build?
- A feel for about how much?
- What kind of testing has it reduced the need for?
- Can you do some effective screening of concepts prior to testing?
- Does the (generally accepted) inability of current RANS technology to reliably predict flight separation onset and progression characteristics effectively minimize the amount of subsonic wind tunnel testing that you can replace with CFD?
- Do you feel you have adequate access to the latest and best CFD capabilities developed by NASA? DoD (where applicable)?
- Are current CFD limitations (in conjunction with facility limitations) an important obstacle standing in the way of the effective implementation of (separation) flow control, laminar flow control, and other promising new technology concepts? Why?
- What do you think is needed before CFD will permit a further significant reduction in the amount of transonic wind tunnel testing needed for vehicle development?
- Do you believe that emerging large-eddy simulation (LES) or direct-eddy simulation (DES) technologies will eventually allow you to make meaningful reductions in the amount of transonic wind tunnel testing you need, for either technology- or product-development efforts? Or, do you believe the direct numerical simulation (DNS) will be needed before you can make any further significant reductions in the amount of transonic wind tunnel testing required?
- What areas, or types of testing, do you believe LES, DES, and/or DNS would allow further significant reductions in the amount of transonic wind tunnel testing required? Any estimates on how long it might be before any of these new technologies are ready and available?
- How would you prioritize needed CFD technology developments versus building any new transonic tunnels? Or making improvements to existing ones?

(13) Do you make a concerted effort to thoroughly document the lessons learned (often the hard way) regarding transonic (and other) wind tunnel test successes and failures that guide new engineers in selecting appropriate test facilities for current issues/problems associated with either existing or new technology implementations? Are these continually updated? Typically, what form are these in?

Supersonic Wind Tunnel Questions

(1) For each vehicle, aircraft, missile, etc., class or type that you are now, or expect to be, involved with, what supersonic tunnels do you (or will you) mainly rely on for your technology- and product-development and testing needs?
- NASA?
- DoD?
- Non-U.S. (Canadian, European, other)?
- Private?
- University?

(2) Are there alternatives and/or backups to these primary facilities available that would allow you to fulfill your testing needs if any of the NASA and DoD (and other) tunnels were not available to you? If so:

- What are they?
- What technical risk factors would be involved?
- What cost and scheduling risks might having to use these alternatives entail?

(3) What facility/testing capability voids exist today that would/might limit your ability to incorporate some of the advanced technology concepts that are being proposed such as advanced flow (separation) control concepts, laminar flow control (passive and active), reduced sonic boom, vehicle geometry simplification concepts, morphing, etc.?

- What new facilities would be necessary to permit incorporation of these advanced technologies into viable new products?
- What thoughts do you have regarding the economic benefits versus costs of such new facilities?

(4) For each vehicle, aircraft, missile, etc., class or type that you are now or expect to be involved with, what are representative *flight* Reynolds numbers (based on wing MAC or other) at important/critical supersonic conditions?

- What are the corresponding Mach numbers?
- What Reynolds numbers are you able to attain with sensibly sized models in the various supersonic wind tunnels that you currently utilize, or plan to utilize?
- What Reynolds numbers do you need/require in order to effectively manage development risk, i.e., preclude significant surprises in flight with existing technologies? With new technologies?

(5) With existing air vehicle aerodynamic technologies, how do wind tunnel flow quality (free-stream turbulence and noise levels, flow angularity, etc.) characteristics influence your determination of what is an acceptable or nonacceptable test facility?

- For general aerodynamic configuration development, especially for smaller vehicles that may have some run/extent of laminar flow in flight?
- What tunnels do you use when excellent tunnel flow quality is necessary?
- Do you think the United States is lacking in wind tunnels with the flow quality needed for some applications? If so, what would you suggest for new facilities? What do you think the technical versus economic arguments would be for such facility developments?

(6) How do you balance flow quality requirements versus Reynolds number requirements if you can't get both?

- For general aerodynamic configuration development?
- Others?

(7) When is having both the necessary flow quality *and* Reynolds number capability an enabling requirement?

- What potentially valuable new technology concepts are having their development and implementation held back by the lack of adequate test facilities that can provide the needed flow quality, Reynolds numbers, etc.?

(8) Is the representative modeling of jet engine (inlet and exhaust) characteristics and effects at supersonic speeds in the wind tunnel an important or critical element in your vehicle development efforts?

- If so, which supersonic tunnels have unique/essential capabilities in this regard?
- Which ones are not really useable/reliable in this regard?
- Do you encounter situations where you have to trade Reynolds numbers, flow quality, etc., capabilities in order to simulate power effects? Or vice versa? What development risks does this impose? Any examples of where this has led to "problems"?
- What advanced technology implementations are being curtailed by propulsion system simulation shortfalls?
- What new capabilities (wind tunnel and propulsion system simulations) do you need to efficiently and effectively develop any potentially promising new concepts/technologies? Any ideas on how these new capabilities could be achieved technically?
- Does the simulation of heat transfer effects ever enter into your choice of acceptable/adequate supersonic wind tunnels?
- Is the inability to simulate/determine heat transfer effects ever a limitation or risk to you?

(9) Considering the numerous "novel" new flow control (e.g., separation onset and progression) concepts under "development," are existing wind tunnel capabilities in the United States adequate to enable the effective and low-risk development and incorporation of these concepts into a range of air vehicle types?

- If not, for which class(es) of vehicles do serious shortcomings exist? What are these deficiencies?
- Is scaling the efficiency of such devices possible, or do you need facilities where full-scale designs can be tested at flight Reynolds numbers with the necessary tunnel flow quality?
- Do you feel that the development of any new facilities to enable the effective and low-risk development and incorporation of these technologies would be economically justified? Why?

(10) Answer questions in (9) but with regard to the effective and low-risk incorporation of laminar flow control technology, either active or passive, for a range of air vehicle classes.

(11) What unsteady flow phenomena (other than flow separation) need to be addressed in supersonic wind tunnel testing of existing and new technologies?

- What capabilities/facilities are needed/required to satisfactorily address flutter, store and stage separation characteristics, etc. for your product line?

- Are there any documented cases where existing facilities have yielded results not representative of flight? If so, could you give us examples?

(12) How have current state-of-the-art computational fluid dynamics capabilities (i.e., Reynolds Averaged Navier Stokes [RANS] with state-of-the-art turbulence models) allowed you to reduce the amount of supersonic wind tunnel test time needed for the development of the supersonic configuration characteristics of the vehicles you develop and build?

- A feel for about how much?
- What kind of testing has it reduced the need for?
- Can you do some effective screening of concepts prior to testing?
- Does the (generally accepted) inability of current RANS technology to reliably predict flight separation onset and progression characteristics effectively minimize the amount of supersonic wind tunnel testing that you can replace with CFD?
- Do you feel you have adequate access to the latest and best CFD capabilities developed by NASA? DoD (where applicable)?
- Are current CFD limitations (in conjunction with facility limitations) an important obstacle standing in the way of the effective implementation of (separation) flow control, laminar flow control, and other promising new technology concepts? Why?
- What do you think is needed before CFD will permit a further significant reduction in the amount of supersonic wind tunnel testing needed for vehicle development?
- Do you believe that emerging large-eddy simulation (LES) or detached-eddy simulation (DES) technologies will eventually allow you to make meaningful reductions in the amount of supersonic wind tunnel testing you need, for either technology- or product-development efforts? Or, do you believe the direct numerical simulation (DNS) will be needed before you can make any further significant reductions in the amount of supersonic wind tunnel testing required?
- What areas, or types of testing, do you believe LES, DES, and/or DNS would allow further significant reductions in the amount of supersonic wind tunnel testing required? Any estimates on how long it might be before any of these new technologies are ready and available?
- How would you prioritize needed CFD technology developments versus building any new supersonic tunnels? Or making improvements to existing ones?

(13) Do you make a concerted effort to thoroughly document the lessons learned (often the hard way) regarding supersonic (and other) wind tunnel test successes and failures that guide new engineers in selecting appropriate test facilities for current issues/problems associated with either existing or new technology implementations? Are these continually updated? Typically, what form are these in?

Hypersonic Wind Tunnel Questions

(1) Which NASA space access and exploration programs have you either been involved with, are presently involved within, or plan to be involved with?

- Shuttle enhancements and safety upgrades?
- Alternate access to Space Station, such as Orbital Space Plane?
- 2nd-generation reusable launch vehicles (RLVs)?
- 3rd-generation RLVs?
- Hypersonic cruise?
- Hyper-X?
- X-30, X-33, X-34, X-37, X-38, X-40, X-43?
- Two-stage to orbit?
- Others?

(2) Similar questions (1) for DoD and DARPA space/hypersonic vehicles, missiles, etc.?

- Hypersonic Deep Attack?
- DARPA Hy-Fly?
- Are there others that you can talk about?
- Others that you can't talk about?

(3) What are the primary vehicle (and other) aerodynamic requirements for ground-based testing (i.e., hypersonic wind tunnel) for the aforementioned air vehicles, missiles, etc.?

- In the research phase?
- In the (preliminary) development phase?
- In the production design stage?

(4) What are the critical "flow physics" characteristics that you need to (or certainly would like to) simulate in ground test facilities and/or flight test in order to achieve the desired aerodynamic and aerothermodynamic flight characteristics for the aforementioned air vehicles, missiles, etc.?

- Boundary layer transition characteristics?
  –Determination and control?
- Shockwave-viscous and/or shock-shock interactions?
- Viscous layer separation and reattachment?

–Flow control?
- Boundary layer diversion characteristics?
- Interacting flow fields (e.g., stage separation)?
- Aero heating characteristics (ascent and reentry)?
- Chemically reacting or nonreacting?
- Base flow (and other separated flow) regions?
- Aero/aeropropulsion interaction?
- Enthalpy levels?
- Radiation and ionization effects?
- Various molecular regimes (rarified, transitional, continuum)?
- Other?

(5) Which "absolute" quantities are important to simulate in order to effectively capture the controlling "flow physics"?
- Reynolds number?
- Free-stream disturbance/noise levels?
- Temperature levels?
- Molecular regimes?
- Enthalpy levels?
- Others?

Why? Or why not?

(6) Which existing *hypersonic* wind tunnels do you deem essential for providing the (best currently available) simulation capabilities needed for the successful development of the previously listed vehicle, missile, etc., programs/categories?
- NASA Langley
  - –8-Foot High Temperature Tunnel (M = 4, 5, 7)?
  - –20-Inch Mach 6 Air Tunnel?
  - –Mach 6 Quiet Tunnel?
  - –15-Inch Mach 6 Hi Temp Air?
  - –31-Inch Mach 10 Air Tunnel?
  - –20-Inch CF_4 Tunnel (M = 13–18)?
  - –22-Inch Mach 15/20 Helium Tunnel (mothballed)?
  - –Hypersonic Pulse Facility?
  - –Others?
- NASA Glenn
  - –Plum Brook Hypersonic Tunnel Facility?
- Arnold Engineering and Development Center
  - –Hypervelocity Wind Tunnel 9?
  - –Von Karman Gas Dynamics Facility Hypersonic Wind Tunnel A?
  - –Von Karman Gas Dynamics Facility Hypersonic Wind Tunnel B?
  - –Von Karman Gas Dynamics Facility Hypersonic Wind Tunnel C?
- Private
  - –Aero Systems Engineering Channel 9?
  - –Boeing B30 Hypersonic Shock Tunnel?
  - –Allied Aerospace (GASL) NASA HYPULSE?
  - –Calspan Large Energy National Shock Tunnel?
- Foreign
  - –ARA Hypersonic Wind Tunnel?
  - –ONERA S4MA?
  - –ONERA F-4?
  - –DNW/DLR RWG?
  - –Various TsAGI Facilities (T-113, 116, 117, IO-2, ST-1, VAT-3, T-131)?

(7) What are the critical advantages of these hypersonic wind tunnels that you have considered, and, also, what are the critical limitations?
- Do you consider some of these as having redundant capabilities, and, if so, which are your preferred facilities? Why?

(8) What new hypersonic wind tunnel testing capabilities are necessary to enable the low-risk development of noted programs/concepts?
- What additional "flow physics" simulation capabilities do you require?

(9) What hypersonic wind tunnel testing capabilities are lacking that necessitate flight-test development programs (prior to commitment)?

(10) Which subsonic, transonic, and supersonic wind tunnels do you deem as essential for the low-risk development of the programs/concepts identified in (1) and (2)? Why?
- What are the important "flow physics" simulations needed?
- What did the NTF testing of the Shuttle ascent configuration tell us in terms of the need for flight–Reynolds number simulation?

(11) What role do current state-of-the-art computational fluid dynamics capabilities presently play in the development of (successful) hypersonic air vehicles, missiles, etc.?

- Have CFD development to date enabled any significant reductions in the amount of ground testing requirements? How?
- What important "flow physics" characteristics can you adequately predict or account for now, and which ones remain elusive? Attached flows, separated flows, etc.?
- What important/critical CFD developments are needed to permit further significant reductions in the amount of ground (and flight) testing required?
- What new technology is likely required for these, and how long do you believe it may take to develop such capabilities? Years? Decades?
- How would you prioritize new/improved facility development efforts versus the development of new/advanced CFD capabilities?

Hypersonic Propulsion Integration Questions

(1) For each vehicle, missile, etc., class or type that you are now, or expect to be, involved with, what specific test facilities do you (or will you) mainly rely on for your technology- and product-development and testing needs?

- NASA?
- DoD?
- Private?

(2) Are there alternatives and/or viable backups to these primary facilities available that would allow you to fulfill your testing needs if any of the NASA and DoD (and other) test facilities were not available to you? If so:

- What are they?
- What technical risk factors would be involved?
- What cost and scheduling risks might having to use these alternatives entail?

(3) What facility/testing capability voids exist today that would/might limit your ability to incorporate some of the advanced technology concepts?

- What new facilities would be necessary to permit incorporation of these advanced technologies?

(4) What are the critical "flow physics" characteristics that you need to (or certainly would like to) simulate in ground test facilities and/or flight test in order to achieve the desired aerodynamic and aerothermodynamic flight characteristics for the aforementioned air vehicles, missiles, etc.?

- Boundary layer transition characteristics?
  –Determination and control?
- Shockwave-viscous and/or shock-shock interactions?
- Viscous layer separation and reattachment?
- Aeroheating characteristics?
- Chemically reacting or nonreacting?
- Enthalpy levels?
- Real gas effects?
- Other?

(5) Which "absolute" quantities are important to simulate in order to effectively capture the controlling "flow physics"?

- Reynolds number?
- Free-stream disturbance/noise levels?
- Temperature levels?
- Enthalpy levels?
- Others?

Why? Or why not?

(6) Which existing hypersonic propulsion-system development facilities do you deem essential for providing the (best currently available) simulation capabilities needed for the successful development of the propulsion systems required for the initially listed vehicle, missile, etc., programs/categories?
For turbojets, ramjets, scramjets, and combined/combination cycle?

- NASA Langley
  –8-Foot High Temperature Tunnel?
  –Arc-Heated Scramjet Test Facility?
  –Combustion-Heated Scramjet Test Facility?
  –Others?
- NASA Glenn
  –Plum Brook Hypersonic Tunnel Facility?
  –Propulsion Systems Laboratory?
  –Others?
- Arnold Engineering and Development Center
  –Aero Propulsion Test Unit?

–G-range (scramjet projectile testing)?
–Others?
• NASA Ames
–High Speed Arc Tunnel
–Other?
• Private?
• Foreign?

(7) What role would current state-of-the-art computational fluid dynamics capabilities play in the development of (successful) propulsion integration concepts?
• What important "flow physics" characteristics can you adequately predict or account for now, and which ones remain elusive?
• What important/critical CFD developments are needed to permit reductions in the amount of ground (and flight) testing required?
• What new technology is likely required for these, and how long do you believe it may take to develop such capabilities? Years? Decades?
• How would you prioritize new/improved facility development efforts versus the development of new/advanced CFD capabilities?

(8) Overall, what would be your general strategy for employing a combination of hypersonic test facilities, computational fluid dynamics, flight test, or other means to develop a hypersonic propulsion integration vehicle/missile?

Direct-Connect Propulsion Facility Questions

Assumptions/Exclusions
• Hypersonic propulsion integration test facilities are a separate category and are not to be addressed here.
• Issues associated with what NASA Glenn research center often refers to as its propulsion wind tunnels, i.e., the 10×10-Foot Supersonic Wind Tunnel and the 8×6-Foot Transonic Wind Tunnel, are presumed to have been addressed in responses to the subsonic, transonic, and supersonic wind tunnel questionnaires.
• Inlet and nozzle development in wind tunnels are assumed to be addressed in the appropriate wind tunnel categories.

Facilities Included in This Air-Breathing Propulsion Test Facilities Category
• Engine test cells/stands such as the NASA Glenn Propulsion System Lab, AEDC C, J, SL, and T facilities, industry facilities, and European facilities.
• Engine component test facilities such as NASA Glenn Engine Component Research Laboratories and the Advanced Subsonic Combustion Rig.
• Acoustic test facilities/anechoic chambers such as NASA Glenn Aero-Acoustic Propulsion Laboratory and Edwards AFB Chamber.
• Vectored-thrust engine/nozzle test stands, etc., for STOVL applications, including MATS (Multiaxis Test Stand), NASA Glenn Powered Lift Rig, European facilities, etc.
• Other?

Questions
(1) For each vehicle, aircraft, missile, etc., class or type that you are now, or expect to be, involved with, which air-breathing propulsion test facility types do you require and/or rely on for your technology- and product-development testing needs?

(2) For each facility type that you require for your technology- and product-development efforts (for each vehicle and/or missile type or class), which facilities (that exist today or are planned) will you mainly rely on?

(3) Are there alternatives and/or backups to these "primary" facilities available to you that would allow you to fulfill your testing needs if any of the primary facilities (NASA, DoD, or others) that you identified become unavailable to you?
• What are they?
• What technical risk factors would be involved?
• What cost and scheduling risks might having to use these alternatives entail?

(4) What are critical facility/testing limitations or voids that exist today in facilities that you currently use, or plan to use, that would seriously hinder your ability to incorporate (identified) advanced technology concepts?
• What modified or new facilities would be necessary to permit incorporation of these advanced technologies into viable new products?
• Do any of these capabilities exist anywhere else (in the world) that you could use?
• Any thoughts on how to justify the costs associated with identified new facility requirements?

(5) Have current state-of-the-art computational fluid dynamics capabilities (i.e., Reynolds Averaged Navier Stokes with state-of-the-art turbulence models) allowed you to reduce the amount of air-breathing propulsion system testing needed for the development of the vehicle and/or missiles you develop and build?

- A feel for about how much?
- What kind of testing has it reduced the need for?

(6) Do you make a concerted effort to thoroughly document lessons learned regarding air-breathing propulsion test facility successes and failures that guide new engineers in selecting appropriate test facilities for current issues/problems associated with either existing or new technology implementations? Are these continuously updated? Typically, what form are these in?

APPENDIX E

Construction Times and Costs for Major Test Facilities

Facility investments and shared support must reflect the dynamics of aeronautics research and development and the possible role of test technologies and facilities as enablers. Major test facilities such as wind tunnel and propulsion test facilities are major investments (ranging from hundreds of millions to billions) and long lead times.

We identified 26 of the 31 NASA facilities that fall within the scope of this study in the NASA Real Property Database. The book value of these test facilities, that is, the simple sum of unadjusted dollars invested in past years in facility construction or modernization, amounted to about $0.9 billion dollars. Because, in many cases, decades have past since construction, the book value is significantly lower than the cost it would take to build the facilities today.

The current replacement value (CRV) of these 26 test facilities totaled about $2.5 billion in the NASA Real Property Database. The CRV is derived by looking at similar types of buildings (e.g., usage, size) within the *Engineering News Magazine*'s construction economics section. The magazine uses a 20-city average to produce rough estimates of how much a building would cost to replace. Most NASA finance and facilities people believe that this average underestimates the actual cost of replacing WT/PT facilities, since they are more complex buildings than the "similar" building types available through engineering economics. Unfortunately, NASA has not found a better metric to compare buildings across the various field centers

Finally, the construction estimates for the large subsonic and transonic facilities proposed in the National Facility Study (1994) ran in the $2–3 billion range (depending on the exact configuration being discussed).

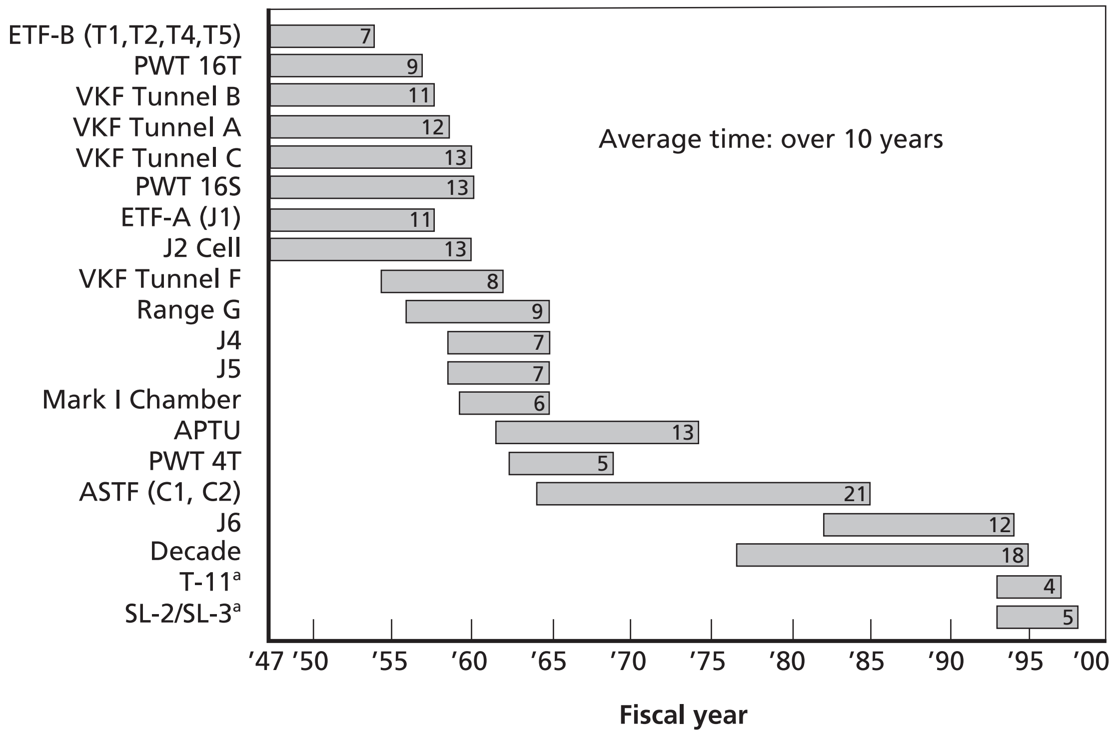
Construction time for a major test facility has averaged more than 10 years in the past[1] (see, for example, AEDC [Arnold Engineering and Development Center] data in Figure E.1)—not counting the years it takes to develop the facility technology, defend the program, and acquire funding from Congress.

As a result, there are significant risks associated with premature decisions regarding research, development, test, and evaluation (RDT&E) test facilities. Building a new facility before having thoroughly analyzed the needs justification or knowing the right design to pursue can result in problems exemplified by the Ames 12-Foot.

Conversely, closing a facility without sufficient long-range planning that will survive the natural budgetary ebbs and flows from current administrations, congressional leadership,

[1] It is unclear, however, to what extent construction time can be compressed for high-priority facilities in a crisis or how much additional funds would be required.

Figure E.1
Major Test Facility Construction Times at AEDC



[a]Acquired through FY03 BRAC
SOURCE: AEDC.
RAND *TR134-E.1*

and vehicle constructions and needs (let alone the uncertainty surrounding research breakthroughs) requires careful planning and long-term support for RDT&E tools despite the attractiveness of short-term gains from closing facilities.

Previous calls for new large, productive, high-Rn facilities (subsonic and transonic) do not match current market drivers of low utilization because of high costs.

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