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# Wind Tunnel and Propulsion Test Facilities

## An Assessment of NASA's Capabilities to Serve National Needs

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# Summary

This monograph reveals and discusses the National Aeronautics and Space Administration's (NASA's) wind tunnel and propulsion test facility management issues that are creating real risks to the United States' competitive aeronautics advantage.

## Introduction

Wind tunnel (WT) and propulsion test (PT) facilities[1] continue to play important roles in the research and development (R&D) of new or modified aeronautic systems and in the test and evaluation (T&E) of developmental systems. The nation has invested about a billion dollars (an unadjusted total) in these large, complex facilities (some dating from the World War II era), which has created a testing infrastructure that has helped secure the country's national security and prosperity through advances in commercial and military

[1] Throughout this monograph, 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.

aeronautics and space systems. Replacing many of these facilities would cost billions in today's dollars.

Many of these test facilities were built when the United States was researching and producing aircraft at a higher rate than it does today and before advances in modeling and simulation occurred. This situation raises the question of whether NASA needs all the WT/PT facilities it has and whether the ones NASA does have serve future needs. In fact, over the past two decades, NASA has reduced its number of WT/PT facilities by one-third. More recently, the agency has identified additional facilities that are now in the process of being closed. In addition, some of the remaining facilities are experiencing patterns of declining use that suggest they too may face closure.

As a result, Congress asked NASA for a plan to revitalize and potentially consolidate its aeronautical T&E facilities to make U.S. facilities more technically competitive with state-of-the-art requirements. Faced with Congress's request and with ongoing budgetary pressures from the Office of Management and Budget (OMB), NASA asked the RAND Corporation to clarify the nation's WT/PT facility needs and the continuing place that NASA's test facilities have in serving those needs, as well as to identify any new investments needed and excess capacities. NASA requested that RAND focus the study on the needs for large (and, thus, more expensive to build and operate) test facilities in six types of WT/PT facilities as well as to identify any management issues they face.

RAND conducted its research from June 2002 through July 2003. The study methodology involved a systematic review and analysis of national research, development, test, and evaluation (RDT&E) needs, utilization trends (historical and projected), test facility capabilities, and management issues. This analysis and its findings focused on answering four basic research questions:

1. What are the nation's current and future needs for aeronautic prediction capabilities, and what role do WT/PT facilities play in serving those needs?

2. How well aligned are NASA's portfolio of WT/PT facilities with national needs?
3. What is the condition (or "health") of NASA's portfolio of WT/PT facilities?
4. How should NASA manage its portfolio of WT/PT facilities?

**Study Activities**

To answer these questions, we conducted intensive and extensive interviews with personnel from NASA headquarters; personnel from 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.

In addition to RAND 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 aeronautic testing needs and various national and international facilities.

Finally, the study 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 or 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]

Also, as *enabling infrastructures*, WT/PT facility operations are not funded directly by specific line items in the NASA budget.[3] 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 facility 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 in that 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 because of program budget constraints. Thus, when a needed facility is closed because of a lack of funding, there is a disconnect between current funding and prudent engineering need, indicating that the commercial and federal budget processes may be out of step with the full cost associated with research and design of a particular vehicle class and indicating a lack of addressing long-term costs and benefits.

Finally, while the study's focus was on national needs and NASA's WT/PT facility infrastructure, national needs are not dictated or met solely by NASA's test infrastructure; DoD, U.S. industry, and foreign facilities also serve many national needs. However, 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 infrastructures.* Based on our findings, such a broader study is important and warranted.

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[2] Specific projects and plans were obtained from NASA, Office of Aerospace Technology (2001; 2002); NASA (2001; 2003); The 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.

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

## What Are the Nation's Current and Future Needs for Aeronautic Prediction Capabilities, and What Role Do WT/PT Facilities Play in Serving Those Needs?

Although applied aeronautics encompasses relatively mature science and engineering disciplines, there is still significant art and empirical testing involved in predicting and assessing the implications of the interactions between aeronautic vehicles and the environments through which they fly. Designers are often surprised by what they find in testing their concepts despite decades of design experience and dramatic advances in computer modeling and simulation known as computational fluid dynamics (CFD). This is, of course, especially true for complex new concepts that are not extensions of established systems with which engineers have extensive practical design and flight experience. But even improving the performance at the margin of well-established and refined designs—for example, commercial jet liners in areas such as reduced drag, fuel efficiency, emissions, noise, and safety (e.g., in adverse weather)—depends on appropriate and sufficient WT/PT facility testing.

Insufficient testing or testing in inappropriate facilities can lead to erroneous estimations of performance. Missed performance guarantees can impose extremely costly penalties or redesign efforts on airframe manufacturers, overly conservative designs from low estimations prevent trade-offs such as range for payload, and even a seemingly small 1 percent reduction in drag equates to several million dollars in savings per year for a typical aircraft fleet operator.[4]

For engineers to predict with sufficient accuracy the performance of their vehicles during design and retrofit, they need a range of capabilities, including high Reynolds number (Rn),[5] flow quality,

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[4] See Mack and McMasters (1992) and Crook (2002).

[5] The Reynolds number is a nondimensional parameter describing the ratio of momentum forces to viscous forces in a fluid. The Mach number is a more familiar nondimensional parameter, describing the ratio of velocity to the sound speed in the fluid. When the flows around similarly shaped objects share the same nondimensional Rn and Mach parameters, 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 co-

size, speed, and propulsion simulation and integration. As discussed below, these capabilities cannot be met by a single test facility but rather require a suite of facilities.

Also, *while CFD has made inroads in reducing some empirical test requirements capabilities, this technology will not replace the need for test facilities for the foreseeable future.* Flight testing complements but does not replace WT/PT facilities because of its high costs and instrumentation limitations.[6] The aeronautic engineering community does not have well-accepted handbooks of facility testing "best practices" or even rules of thumb from which to deduce testing requirements, nor is it possible from historical data to accurately predict returns on specific facility testing in terms of programmatic cost savings or risk reduction.

Thus, *aeronautic maturity does not nullify the need for test facilities but in fact relies on the availability and effective use of test facilities to provide important capabilities.* The nation continues to need general-purpose WT/PT facilities across all speed regimes, as well as for specialty tests. These facilities advance aerospace research, facilitate vehicle design and development, and reduce design and performance risks in aeronautic vehicles.

## How Well Aligned Are NASA's Portfolio of WT/PT Facilities with National Needs?

NASA's WT/PT facilities are generally consistent with the testing needs of NASA's research programs, as well as with those of the broader national research and development programs. Currently, redundancy is minimal across NASA. Facility closures in the past decade have eliminated almost a third of the agency's test facilities in the categories under review in this study. In nearly all test categories,

efficients will apply (Batchelor, 1967). Airflow behavior changes nonlinearly and unpredictably with changes in Rn. Thus, it is important to test the flow conditions at flight (or near-flight) Rn to ensure that the flows behave as expected and that conditions such as undesired turbulence, separations, and buffeting do not occur.

[6] See, for example, Wahls (2001).

NASA has a single facility that serves the general- or special-purpose testing needs, although some primary facilities also provide secondary capabilities in other test categories. We found two noncritical WTs: (1) the Langley 12-Foot Subsonic Atmospheric WT Lab, which is redundant to the Langley 14×22-Foot Subsonic Atmospheric WT, and (2) the Langley 16-Foot Transonic Atmospheric WT, which is generally redundant to the Ames 11-Foot Transonic High-Rn and Langley National Transonic Facility WTs run in low-Rn conditions.

There are gaps in NASA's ability to serve all national needs. In most of these cases, though, DoD or commercial facilities step in to serve the gaps.

Finally, some of NASA's facilities that serve national needs have been or are in the process of being mothballed. While mothballing an important facility is preferred to abandonment, mothballing involves the loss of workforce expertise required to safely and effectively operate the facility. Thus, mothballing is not an effective solution for dealing with long periods of low utilization, and it puts facilities at risk.

## What Is the Condition (or "Health") of NASA's Portfolio of WT/PT Facilities?

In looking at the condition, or health, of NASA's WT/PT facilities, two of the three key dimensions are (1) how *technically competitive* the facilities are and (2) how *well utilized* they are. Judged by those measures, NASA's portfolio is generally in very good condition. More than three-fourths of NASA's WT/PT facilities are competitive and effective with state-of-the-art requirements. In addition, more than two-thirds are well utilized. Overall, about two-thirds are both technically competitive and well utilized, with this number varying across the categories of test facilities.

However, there is room for improvement, especially in the high-Rn 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 concerning 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 hypersonic testing, will require additional research to develop viable facility concepts for future investment consideration.

Finally, using a third dimension of health status—*financial health*—we find that the full-cost recovery (FCR) accounting practice imposed by NASA on the centers has serious implications for the financial health of those facilities that are underutilized (about one-third of the facilities in general, with variation across the test facility category types). Average-cost-based pricing, decentralized budgeting, poor strategic coordination between buyers and providers of NASA WT/PT facility services, and poor balancing of short- and long-term priorities inside and outside NASA are creating unnecessary financial problems that leave elements of the U.S. WT/PT facility capacity underfunded. With declining usage and FCR accounting, these facilities run the risk of financial collapse.

## How Should NASA Manage Its Portfolio of WT/PT Facilities?

NASA's primary management challenges break down into two questions. First, how can NASA identify the *minimum set* of WT/PT facilities important to retain and manage to serve national needs? Facilities that are in the minimum set should be kept, but those that are not in the set could be eliminated (and, thus, constitute excess capacity from a national strategic point of view). Second, what financial concerns and resulting management steps are needed to manage the facilities within the minimum set?

### Identifying the Minimum Set

Based on our analysis, 29 of 31 existing NASA WT/PT facilities constitute the minimum set of those important to retain and manage to serve national needs. Thus, the test complex *within* NASA is mostly "right sized" to the range of national aeronautic engineering needs.

It is important to bear in mind that, while not the case within NASA, a few of NASA's facilities are redundant when considering the technical capabilities of the larger set of facilities maintained by commercial entities and by the DoD's AEDC. Whether these redundancies amount to the "unnecessary duplication" of facilities prohibited by the National Aeronautics and Space Act of 1958 was beyond the scope of this study. Further analysis of technical, cost, and availability issues is required to determine whether WT/PT facility consolidation and right-sizing across NASA and AEDC to establish a national reliance test facility plan would provide a net savings to the government and result in a smaller minimum set of WT/PT facilities at NASA.

Congress has expressed interest in collaboration between NASA and the DoD.[7] NASA and the DoD (through the National Aeronautics Test Alliance—NATA) have made some progress in their partnership,[8] but NASA's recent unilateral decision to close two facilities at Ames without high-level DoD review shows that progress has been spotty. Some in industry have expressed an interest in exploring collaborative arrangements with NASA and hope that this study will reveal to others in industry the risks to NASA's facilities and the need for industry to coordinate its consolidations with those of NASA and the DoD. Our study provides insights into the problem but offers only glimpses into the wider possibilities and issues surrounding broader collaboration.

### Financial Support

The key management challenge remaining for NASA is to identify shared financial support to keep its minimum set of facilities from financial collapse given the long-term need for these facilities.

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[7] See, for example, the GAO report on NASA and DoD cooperation entitled *Aerospace Testing: Promise of Closer NASA/DoD Cooperation Remains Largely Unfulfilled*, 1998.

[8] For example, NATA has produced a number of joint NASA and DoD consolidation studies. See NATA (2001a; 2001b; 2002).

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, has left Ames WTs without support beyond user testing fees. Thus, Ames WT/PT facilities are vulnerable to budgetary shortfalls when utilization falls. Two Ames facilities that are unique and needed in the United States have already been mothballed and slated for closure as a result.

If NASA management is not proactive in providing financial support for such facilities beyond what is likely to be available from FCR pricing, then the facilities are in danger of financial collapse. In the near term, this market-driven result may allow NASA to reallocate its resources to serve more pressing near-term needs at the expense of long-term needs for WT/PT facilities. Given 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, the right-sizing NASA has accomplished to date, the indeterminate costs to decommission or eliminate these facilities, the significant time and money that would be required to develop new replacement WT/PT facilities, and the relatively modest resources required to sustain these facilities, care should be taken to balance near-term benefits against long-term risks. Collaboration, reliance, and ownership transferal options for obtaining alternative capabilities in lieu of certain facilities are possible, but even if these options are exercised, many NASA facilities will remain unique and critical to serving national needs. 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.

## Policy Issues, Options, and Recommendations

Table S.1 lays out and summarizes the main policy issues identified in the study along with the decision space for those issues and our assessment of the viability of those options. Nearly all options are specifically recommended or not recommended. One non-recommended option related to investments could be pursued, but it is unclear how viable it is in today's financial climate.

Note that the issues and options tend to be interrelated. For example, the determination of which facilities are important to keep is related to the question of what to do with low-utilization facilities. The recommended options are also related. For example, developing a long-term vision and plan for aeronautic testing, reviewing the technical competitiveness of facilities, and sharing financial support for facilities with users are interrelated.

The most critical issue is for NASA headquarters leadership to **develop a specific and clearly understood aeronautics test technology vision and plan**, to continue to support the development of plans to very selectively consolidate and broadly **modernize existing test facilities**, and to proscribe **common management and accounting directions** for NASA's WT/PT facilities. This vision cannot be developed in isolation from other critical decisions facing the nation. It must be informed by the aeronautic needs, visions, and capabilities of both the commercial and military sectors supported by NASA's aeronautical RDT&E complexes.

Given the inherent inability to reliably and quantitatively predict all needs for RDT&E to support existing programs much beyond a few months out, and the trends indicating a continuing decline in needed capacity to support these needs for the foreseeable future, **long-term strategic considerations must dominate**. If this view is accepted, then NASA must find a way to sustain indefinitely and, in a few cases, enhance its important facilities (or seek to ensure reliable and cost-effective alternatives to its facilities) as identified in this study.

Beyond this overarching recommendation, we propose the following, which reflect the entries shown in Table S.1:

- **NASA should work with the DoD to analyze the viability of a national reliance test facility plan,** since this could affect the determination of the future minimum set of facilities NASA should continue to support.

**Table S.1**
**Key Policy Issues, Options, and Recommendations**

| Strategy | Technical Need | Facilities Needed | | Operating Costs | Investments |
|---|---|---|---|---|---|
| **Issue: How should testing be addressed strategically?** | **Issue: How should aeronautic testing needs be met?** | **Issue: Which facilities should NASA keep in its minimum set?** | **Issue: What to do with low-utilization facilities?** | **Issue: How should the facilities be funded?** | **Issue: What future investments should be made?** |
| **1. Develop a NASA-wide aeronautics test technology vision and plan**<br>**2. Work with the DoD to analyze the viability of a national test facility plan** | 1. Replace facility testing with CFD<br>2. Replace facility testing with flight testing<br>3. Use facility testing exclusively<br>**4. Use appropriate mix of facility, CFD, and flight testing** | 1. Keep all facilities that align with national needs<br>**2. Leave out aligned facilities that are weakly competitive, redundant, and poorly utilized**<br>3. Leave out all facilities technically similar to those in the DoD | 1. Close when utilization is low<br>2. Mothball when utilization is low<br>**3. Reassess long-term needs and keep those strategically important**<br>4. Keep all facilities regardless of utilization | 1. Recover all costs from users<br>**2. Share support between users and NASA institutional funding**<br>3. Pay all costs through institutional funding so testing is free to users | **1. Eliminate backlog of maintenance and repair (BMAR)**<br>**2. Conduct hypersonics test facility research**<br>*3. Pursue high-productivity, high-Rn subsonic and transonic facilities*<br>**4. Continued investments in CFD research** |

NOTES: **Bold = Recommended**; *Italics = Unclear*; Roman = Not Recommended.

- NASA should **continue to pursue all three complementary approaches—facility, CFD, and flight testing**—to meeting national testing needs. At this point, none can cost-effectively meet testing needs on its own.
- NASA should **identify the minimum set of test facilities important to retain and manage to serve national needs**. The facilities that do not belong in the minimum set are those that, despite their alignment with national needs, are weakly competitive, redundant, and poorly utilized. Further analysis of technical, cost, and availability issues are required to determine whether facility consolidation and right-sizing across NASA and the DoD would provide a net savings to the government.
- Utilization data is only one (nonexclusive) factor in determining what facilities to keep in the minimum set. In particular, utilization helps to decide what to do with redundant facilities. Thus, **poorly utilized facilities should be reassessed for strategic, long-term needs** rather than being eliminated out of hand; only those that do not survive that assessment are candidates for closure or mothballing. *Mothballing incurs the loss of important workforce expertise and knowledge.*
- NASA leadership should **identify financial support concepts to keep its current minimum set of facilities healthy for the good of the country**. It appears reasonable to ask users to pay for the costs *associated with their tests* (i.e., to pay for the short-term benefits), but forcing them to pay *all* operating costs (including long-term priorities such as the costs for facility time they are not using) through FCR *direct test pricing* (as is done at Ames) will further discourage use and endanger strategic facilities by causing wide, unpredictable price fluctuations in a world where government and commercial testing budgets are under pressure and are set years in advance. Also, we do not recommend setting the prices for user tests to zero because it closes one channel of information to users about the costs they are imposing on the infrastructure, can encourage overuse, and therefore cause limits on the availability of funding.

It is important to retain perspective on the magnitude of NASA's WT/PT facility costs relative to the investment value of the aerospace vehicles they enable or support. **While the approximate $125–130 million WT/PT operating cost is a significant sum, it pales in significance to NASA's overall budget of about $15,000 million[9] and the $32,000–58,000 million the United States invests in aerospace RDT&E each year.**[10] NASA should continue to closely reassess WT needs and ensure that excesses are not present. However, the agency should keep in mind the connection between these costs and the benefits they accrue. Engineering practices indicate that both the short- and long-term benefits are worth the cost in terms of the vehicles they enable, the optimization gains, and the reductions in risk to performance guarantees—even if short-term budgets are not currently sized to support the long-term benefits.

In terms of **investments**, we recommend the following:

- The $128 million **BMAR** at NASA facilities should be eliminated.
- Serious research challenges in **hypersonic air-breathing propulsion** may require new facilities and test approaches for breakthroughs to occur. This will require research in test techniques to understand how to address these testing needs and ultimately to look at the viability of hypersonic propulsion concepts being explored.
- To remain technically competitive, it makes sense to further consider investments in high-productivity, high-Rn subsonic and transonic facilities; however, current fiscal constraints make it unclear whether such investments should be pursued today.

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[9] NASA 2002 Initial Operating Plan budget figures.

[10] Federal aerospace procurements and R&D expenditures in the period of FY1993–FY2001 ranged from a high of $58 billion in FY1994 to a low of $32 billion in FY2001 (Source: RAND research by Donna Fossum, Dana Johnson, Lawrence Painter, and Emile Ettedgui published in the *Commission on the Future of the United States Aerospace Industry: Final Report* [Walker et al., 2002, pp. 5–10]).

- Because of significant progress and utility, **continued investment in CFD** is recommended.

Beyond the general recommendations discussed above and highlighted in Table S.1, **NASA should focus on specific WT/PT facilities that require attention.** Financial shared support is most critical right now for the facilities at Ames: the 12-Foot, the National Full-Scale Aerodynamics Complex (NFAC), and the 11-Foot tunnels. Until an alternative domestic high-Rn subsonic capability can be identified, the Ames 12-Foot Pressure Wind Tunnel should be retained in at least a quality mothball condition. The NFAC is strategically important, especially for the rotorcraft industry, and needs immediate financial support to prevent the facility from abandonment at the end of FY2004. The Ames 11-Foot High-Rn Transonic facility currently provides excess capacity, but NASA should work with the DoD to establish long-term access to and clarified pricing for the AEDC 16T before considering whether to remove the Ames 11-Foot from the minimum set of needed facilities. Other facilities with unhealthy ratings also require attention, including the Langley Spin Tunnel, the Glenn 8×6-Foot Transonic Propulsion Tunnel, and the Ames 9×7-Foot Supersonic Tunnel.

In addition, **NASA should continue to explore options to preserve the workforce.** While our principal study focus has been on the test facilities themselves, these complex facilities become useless without trained personnel to operate them. Stabilizing NASA's institutional support for test facilities will help ensure that today's dedicated and competent workforce will be able to pass their skills on to future generations.

In conclusion, NASA has played critical roles in advancing the aeronautic capabilities of the country and continues to have unique skills important across the military, commercial, and space sectors —in terms of both research and support of our ability to learn about and benefit from advanced aeronautic concepts. Major wind tunnel and propulsion test facilities continue to have a prominent position in supporting these objectives. Unless NASA, in collaboration with the DoD, addresses specific deficiencies, investment needs, budgetary difficulties, and collaborative possibilities, the United States faces a real risk of losing the competitive aeronautics advantage it has enjoyed for decades.