Aeronautical Facilities: Assessing the National Plan for Aeronautical Ground Test Facilities

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AUTHORS

Aeronautics and Space Engineering Board, National Research Council

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PREFACE

The United States is engaged in a serious global economic competition with the established economies of Europe and Japan and with emerging industrial economies elsewhere in Asia and the former states of the Soviet Union. This competition includes the aerospace market, a segment of the economy that the United States has dominated and from which it has profited for decades. The National Facilities Study (NFS)[1] documents that foreign competition in aeronautics has reduced U.S. market share in commercial aircraft by 30 percent during the past 25 years. If other nations achieve a higher level of technology in this area, erosion of the U.S. market share is likely to accelerate, with accompanying reductions in balance of trade and jobs.

Wind tunnel ground test facilities are used to develop, evaluate, and verify the performance of new aircraft, particularly with regard to lift, drag, and moment characteristics. Wind tunnel testing allows engineers to evaluate analytically derived models and update the design prior to and during flight test, well before production release. The availability of adequate wind tunnel test facilities supported by improved computational modelling will allow aircraft manufacturers to shorten the design cycle, improve the quality and producibility of their final products, and avoid costly changes during production.

In 1992, the National Aeronautics and Space Administration (NASA) opened discussions with the Departments of Defense, Energy, Transportation, and Commerce, and the National Science Foundation regarding the development of a long range plan for aerospace test facilities. The result of these interagency discussions was the formation of the National Facilities Study, which was carried out by one oversight and four task groups, supported by various working groups. Study participants included industry personnel to ensure that product requirements were properly considered by the task group that focused on aeronautical facilities.

During 1993, NASA asked the Aeronautics and Space Engineering Board (ASEB) to review the NFS report. The ASEB subsequently agreed (1) to form an ad hoc committee on space facilities and (2) to independently examine projected requirements for and approaches to the provision of needed aeronautical ground test facilities. This report documents the results of this effort, which responded to the following task elements:

- to review and critique aeronautical research and development (R&D) requirements for subsonic, transonic, propulsion, supersonic, and hypersonic ground test facilities as presented in the final report of the NFS Task Group on Aeronautical R&D Facilities (Volume II of the NFS report);[2]
- to review and critique the recommended facility approaches (including modification, consolidation, or phaseout of existing facilities and construction of new facilities) in the final report of the Task Group on Aeronautical R&D Facilities;
- to consider alternative ways that recommended facility needs might be addressed (e.g., by pooling resources internationally in the construction of new facilities or in new practices that would make the use of foreign facilities more amenable); and
- to assess the priorities presented in the task group's final report.

[1]National Facilities Study. 1994. Volume 2: Task Group on Aeronautical Research and Development Facilities Report. April 29, 1994.

[2]The NSF Task Group on Aeronautical R&D Facilities focused on ground-based aerodynamic and aeropropulsion facilities in order to accommodate limitations on time and resources. The results of the National Facilities Study and the National Aeronautical Test Facilities Study should not be used to assert that types of facilities that were outside the scope of their deliberations are unimportant to the future of the U.S. aeronautics industry, even though such facilities are not discussed in the resulting reports.

Review of detailed design, cost, siting, and programmatic issues were not included within the scope of the ASEB's effort, although this report does contain some general comments on these topics.

This study focused on the aeronautics components of the NFS final report: Volume II, *Task Group on Aeronautical Research and Development Facilities Report* (approximately 450 pages),[3] and Volume II-A, *Facility Study Office on the National Wind Tunnel Complex Final Report* (approximately 1,000 pages).[4] Based on these reports, previous studies by the National Research Council, and other available information, the ASEB studied various approaches for developing the facilities needed by the U.S. aeronautics industry. In some cases, the board endorsed specific options. In other cases, where insufficient data are available, it identified key areas of concern and parameters that government and industry should more fully explore before making final decisions on how to proceed.

The Aeronautics and Space Engineering Board would like to thank those who enabled it to successfully complete this study, particularly H. Lee Beach, Jr., L. Wayne McKinney, and the other members of the NFS Task Group on Aeronautical R&D Facilities; each of the participants in the National Aeronautical Test Facilities workshop (listed in Appendix B); Alexander H. Flax, who served as an advisor to the committee; and the independent reviewers—who must remain anonymous—who critiqued this report prior to final editing and publication.

Bernard L. Koff
Chairman, National Aeronautical Test Facilities Study

[3]Volume II contained separate appendices documenting the results of each working group: the Facility Benchmarking Working Group, which documented the capabilities of operational development wind tunnels; the Aerodynamics and Acoustics Working Group, which studied subsonic, transonic, and supersonic facility requirements; the Strategy Working Group, which examined acquisition strategy, user access policy, and pricing policy; the Propulsion Facilities Working Group; and the Hypersonic Facilities Working Group.

[4]The Facility Study Office was a separate organization consisting of personnel from NASA and the Department of Defense that worked together at Langley Research Center from May through December 1993. It supported the NFS Task Group on Aeronautical R&D Facilities by providing detailed financial and technical assessments of selected low speed and transonic wind tunnel design options.

Copies of Volumes II and II-A of the NFS report should be requested from the National Aeronautics and Space Administration, Office of Public Affairs, Washington, D.C., 20546-0001.

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List of Acronyms and Abbreviations

ADP	Advanced Ducted Propulsor
ASEB	Aeronautics and Space Engineering Board
ASTF	Aeropropulsion Systems Test Facility
CFD	Computational Fluid Dynamics
FSO	Facilities Study Office
GAO	General Accounting Office
NACA	National Advisory Committee for Aeronautics
NAE	National Academy of Engineering
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
NFS	National Facilities Study
R&D	Research and Development
SFC	Specific Fuel Consumption

Executive Summary

At the request of the National Aeronautics and Space Administration and Department of Defense, the Aeronautics and Space Engineering Board (ASEB) of the National Research Council independently reviewed the findings of the interagency National Facilities Study (NFS). In order to make the ASEB report available shortly after the NFS report, the NFS Task Group on Aeronautical R&D Facilities briefed the ASEB periodically during its study. After release of the NFS report, the ASEB held a far-ranging workshop to critique the NFS results. The workshop involved 49 experts in aeronautical technology development; ground test facilities; and, especially, the use and operation of wind tunnels. The purpose of this report is to document and explain the ASEB's assessment of the NFS report, including recommendations for future action.

The conclusions and recommendations of the NFS seem to be supported by factual material wherever it was available, although in some cases they are based on the best judgement of the study participants. The following nine items summarize the ASEB's findings and recommendations. The first five items reinforce key thrusts of the National Facilities Study. The ASEB concurs with each of these items. The last four are recommendations for additional action that go beyond the recommendations of the National Facilities Study.

RECOMMENDATIONS REINFORCING THE KEY THRUSTS OF THE NATIONAL FACILITIES STUDY

1. The ASEB agrees with the NFS report that significant aerodynamic performance improvements are achievable, and the nation that excels in the development of these improvements has the opportunity to lead in the global market for commercial and military aircraft.[1] The highest priority facilities for achieving these performance improvements are new high-productivity, high-Reynolds-number subsonic and transonic development wind tunnels.[2] The NFS report estimates that cruise and take-off/landing performance could be improved by at least 10 percent each. Performance improvements are essential for the U.S. aeronautics industry to maintain or increase market share. Based on the information available to it, the ASEB considers these projected increases in performance to be potentially attainable and believes that the proposed facilities could substantially facilitate such improvements.

These forecast advantages do not include the probable operating and development cost reductions that would accrue to future U.S. military aircraft programs. In addition to direct cost reductions, access to improved ground test facilities would make advanced military aircraft more competitive in the world market, thereby further reducing the defense burden carried by U.S. taxpayers. Foreign sales of U.S. military aircraft result in lower unit costs for U.S. government and foreign purchasers.

2. The ASEB agrees with the NFS report that new high Reynolds number ground test facilities are needed for development testing in both the low speed and transonic regimes to assure the competitiveness of future commercial and military aircraft produced in the United States. The NFS report documents that Reynolds and Mach number performance of the best subsonic and transonic development wind tunnels in the United States and Europe

[1]The National Research Council report *Aeronautical Technologies for the 21st Century* (NRC, 1992) documents historical trends and projects future gains in aircraft performance as a result of technological advances.

[2]Overall priorities are discussed in more detail in Chapter 6 starting on page 44.

are close to parity.[3] However, the average age of major U.S. tunnels is about 38 years, and many of the older U.S. wind tunnels are subject to costly maintenance and breakdown. Furthermore, there are no adequate domestic alternatives for many older U.S. facilities. For example, during the past several years U.S. manufacturers have conducted a large amount of their low speed testing in European facilities during refurbishment of the Ames Research Center 12-foot subsonic wind tunnel, which is 48 years old.

Table ES-1 Proposed Capabilities of New Low Speed and Transonic Wind Tunnels

TUNNEL PARAMETER	LOW SPEED TUNNEL	TRANSONIC TUNNEL
Reynolds Number	20 million at Mach 0.3 (full span model) 35 million at Mach 0.3 (semi-span model)	28.2 million at Mach 1 (full span model)
Mach Number	0.05-0.6	0.05-1.5
Productivity	5 polars per occupancy hour*	8 polars per occupancy hour
Operating Cost	<$1,000/polar	<$2,000/polar
Operating Pressure	5 atmospheres	5 atmospheres
Total Temperature	110°F	110°F at Mach 1
Maximum Power	45 MW	300 MW
Test Section Size	20 ft × 24 ft	11 ft × 15.5 ft
Flow Quality	Low turbulence	Low turbulence
Acoustic Test Capability	Acoustic test chamber	Not applicable

*A polar is a single test run consisting of 25 data points (see Appendix D).

Source: NFS, 1994.

In contrast, European industry has a new government-funded transonic facility coming on-line during 1994 that is expected to significantly outperform any transonic development facilities in the United States in terms of Reynolds number capability. [4] The NFS report examines this situation in detail with regard to the development of new commercial air transports, which have very high flight Reynolds numbers.

More-capable wind tunnels will facilitate improvements in aircraft performance and producibility. However, as documented by the NFS, no wind tunnel in the world meets or can be affordably modified to meet the goals defined by the NFS for development of future transport and military aircraft (see Table ES-1).[5]

The ASEB agrees with the NFS that building the two tunnels as proposed is likely to enable subscale development testing for more than half of the new commercial transport aircraft projected for the next twenty years or so at flight Reynolds and Mach numbers. However, the flight Reynolds numbers of (1) very large commercial transports, (2)high speed civil transports, (3) high performance military aircraft, and

[3]Mach and Reynolds numbers are defined in Appendix D.

[4]The U.S. National Transonic Facility has a Reynolds number capability of 119 million, but its productivity is an order of magnitude less than other large transonic facilities. Thus, even though it has a limited (design-verification) role to play in the development of new aircraft, it is not a "development" wind tunnel. Its primary role is as a research facility.

[5]The NFS initially established a Reynolds number test capability of approximately 30 million as a goal for both the low speed and transonic wind tunnels. After assessing the impact of performance goals on facility design and cost, the NFS recommended accomplishing this goal in the low speed regime using semi-span models. Semi-span models include only the left or right half of an airplane. This increases the Reynolds number capability of a given facility relative to tests using full-span models.

(4) some revolutionary design concepts that might emerge in the future would exceed the capabilities of the proposed tunnels. Thus, the test results for these aircraft would have to be extrapolated to analyze their performance at flight Reynolds number. Nonetheless, this process would generally be more accurate than extrapolations based on data obtained from the less capable tunnels now available. In particular, the new wind tunnels would allow testing models of existing aircraft such as the B-737 and MD-90 at flight Reynolds number. Comparison of wind tunnel and flight data for these aircraft is likely to significantly improve the correlation of wind tunnel and flight data for future designs of conventional aircraft that have flight Reynolds numbers beyond the test limit of the proposed tunnels.

The NFS report recommends taking immediate action to reduce the projected cost ($2.55 billion) and schedule (eight years) of acquiring the proposed low speed and transonic wind tunnels.[6] The ASEB agrees that reducing cost and schedule is an important goal, but it cautions against using management-directed cost and schedule estimates to provide the illusion of achieving this goal.

3. Along with the procurement of new facilities, the ASEB agrees with the NFS that selected upgrades to existing facilities are also essential to adequately support future research and development programs. These upgraded facilities will be important during the interim before new tunnels are operational and, afterwards, to round out the United States' test capabilities matrix. However, facility upgrades cannot alone satisfy future ground test requirements.

In particular, the ASEB endorses the NFS's proposed upgrade to the common 16S/16T drive system at Arnold Engineering Development Center and urges further consideration of additional activities to improve the reliability of the drive-system motors and compressors. In case of failure, major motor repairs could take from four months (to rewind a motor stator) to over three years (for complete motor replacement). Although Arnold Engineering Development Center estimates that motor problems requiring complete replacement are very unlikely, credible accidents such as an electrical arc-over with severe internal motor damage could reduce the operational capability of 16S (and 16T) for up to a year.[7] This would have a severe impact if it occurred at a critical point in an aircraft development program. Additional improvements to the drive system should be carefully considered to reduce the probability of such an occurrence.

4. The ASEB agrees with the NFS that the United States should acquire premier development wind tunnels rather than rely on continued use of European facilities. Over the past 25 years, as European aeronautics technology has risen to equal U.S. technology, the United States' market share in transport aircraft has declined 30 percent. Although market share is a function of many factors, if other nations achieve a higher level of aeronautical technology, erosion of the U.S. market share may accelerate, with accompanying reductions in balance of trade and jobs.[8] Continued advances in aerodynamic technology are necessary to avoid this situation. The proposed facilities represent an investment that is only a small fraction of the potential future gain and will provide an opportunity to enhance U.S. technology development. Acquisition of advanced high-productivity wind tunnels in the United States—where U.S. designers can efficiently coordinate their wind tunnel testing, model building, and computational activities—will improve the effectiveness and

[6]The National Facilities Study included a very detailed costing effort, which is documented in Volume II-A of its final report.

[7]Laster, M.L. June 17, 1994. National Aeronautical Test Facilities Study Information Memorandum. Directorate for Plans and Requirements, Arnold Engineering Development Center. Arnold Air Force Base. Tennessee.

efficiency of the aircraft design and development process.

When aircraft designers introduce a new product, they must determine how far to push available technology before selecting the final design. The nation with the most efficient design-test-redesign process can achieve either (1) a given level of performance sooner or (2) better performance within a given period of time. Inferior, inefficient design or test processes, on the other hand, allow the competition to produce an equal or better product sooner. Slow design and test methodologies also extend the period that manufacturers must fund product development, increasing the costs of bringing new products to market.

Although U.S. designers have access to European facilities, the ASEB believes that the scheduling constraints faced by U.S. users and the inefficiency of conducting transatlantic design and development efforts inevitably delay the introduction of new products. Conversely, European competitors have greater access to better test facilities and, potentially, to the data generated when U.S. aircraft manufacturers use their wind tunnels. In combination with other improvements that industry is making in its design and manufacturing process, the ASEB believes that the construction of advanced development wind tunnels will be an important contribution to the productivity of the U.S. aeronautics industry.

Because of national security concerns, foreign facilities are especially inappropriate for development of military aircraft. The U.S. defense industry is generally limited to U.S. facilities, even if more-capable facilities are available elsewhere.

The NFS report identifies three options for funding the construction of the proposed subsonic and transonic wind tunnels: industry only; a government/industry consortium; and government only. After assessing these options, the NFS “envisioned that the facilities will be constructed primarily with government funding,” and it concluded that “funding by industry alone is not a viable source of capitalization.” However, it also determined that the possibility of obtaining funding jointly from government and industry “could not be ruled out” and it recommended conducting “further studies to look at innovative funding approaches and government/industry consortia arrangements.” The ASEB understands that these studies are underway.

5. The ASEB agrees with the NFS that additional action is necessary to address future requirements for supersonic, hypersonic, and aero-propulsion test facilities. It is not appropriate to immediately proceed with the construction of new supersonic, hypersonic, or aeropropulsion development facilities. Each of these areas, however, will be important to the aeronautics industry of the future. Thus, appropriate action should be taken to ensure that required facilities will be available when necessary.

Supersonic Facilities. The Department of Defense will have continuing needs for supersonic ground testing of new and upgraded military flight vehicles and systems, and NASA's High Speed Civil Transport Program will create additional demands for access to supersonic wind tunnels.

Incorporating supersonic laminar flow characteristics into military and commercial aircraft would significantly reduce drag and surface heating and increase fuel efficiency. However, designing a cost-effective supersonic laminar flow facility to conduct development testing is beyond the current state of the art. Solution of the complex problems involved will require a continued program of theoretical and experimental investigation.

In order to partially address shortfalls in U.S. supersonic facilities regarding productivity, reliability, maintainability, and laminar flow test capabilities, the 16S facility at Arnold Engineering Development Center, which would be used to support development of a first-generation high speed civil transport, should be upgraded. In addition, research should continue on supersonic laminar flow technology and facility concepts.

Hypersonic Facilities. More-capable hypersonic ground test facilities are needed to provide the option for future development of hypersonic vehicles. State-of-the-art technology, however, is not adequate to build major new hypersonic facilities that will have

[8]For a more thorough discussion of the factors affecting the eroding U.S. position in aeronautics, the necessary but insufficient role that advances in technology play, and specific technology advances that are possible and desirable, see *Aeronautical Technologies for the Twenty-First Century* (NRC, 1992), pages 26–34 and the discussions of current industry status, market forecast, and barriers for each of the major speed regimes.

the needed capabilities in areas such as model size, run time, pressure, temperature, and velocity. Therefore, near-term efforts should focus on a program of research to select, develop, and demonstrate the most promising hypersonic test facility concepts. Long-term efforts to build hypersonic development facilities will be contingent upon successful completion of the near-term facility research effort and concurrent efforts to validate future requirements for hypersonic vehicles.

Aeropropulsion Facilities. Aeropropulsion test facilities within the United States have the capability to test current air breathing engines under the operating conditions experienced during take-off, climb, cruise at flight speeds up to Mach 3.8, approach, and landing. Looking to the future over the next 10 to 30 years, air breathing engine test facility requirements will be determined by engine size, type, configuration, and air flow requirements.

The Aeropropulsion System Test Facility at Arnold Engineering Development Center, as currently configured, is adequate for altitude testing of the newest generation of high-bypass engines. However, a 40 percent increase in flow capacity might be required to handle the next generation of ultra-high-bypass, gear-driven propulsor engines such as the PW4000 Advanced Ducted Propulsor. These engines could be certified after the year 2000—if the aircraft manufacturers develop new, larger aircraft requiring such engines. Implementation of facility upgrades for these larger subsonic engines would take four to eight years, so there is time to “wait and see” before deciding how to proceed.

RECOMMENDATIONS GOING BEYOND THOSE OF THE NATIONAL FACILITIES STUDY

As previously indicated, the remaining four items go beyond the recommendations of the National Facilities Study report. These recommendations will (1) reduce risk associated with carrying out the actions recommended by the NFS and (2) facilitate long-term efforts to provide U.S. users with improved aeronautical ground test facilities.

6. The Wind Tunnel Program Office should conduct trade studies to evaluate design options associated with the proposed new low speed and transonic wind tunnels.[9] Facility configuration trade-off studies conducted by the NFS on Reynolds number, productivity, and life cycle cost appear to be sound. However, additional configuration studies should be conducted during the design phase of the wind tunnel program. These assessments should take into account the differences in tunnel and model parameters between subsonic and transonic wind tunnel testing. They should evaluate the merits of the following design options:

- **a. Using a single tunnel to test both the low speed and transonic speed regimes.** While a single tunnel would be unlikely to offer the same capabilities as two separate tunnels, the extent to which performance and operational costs would be compromised should be evaluated in terms of savings in acquisition costs. This assessment should verify the accuracy of projected utilization rates to determine if a single facility could meet the expected demand for test hours.
- **b. Making incremental changes to the tunnel operating pressures (e.g.,from 5 to 5.5 atmospheres).** Increasing wind tunnel operating pressure would allow facility size and cost reductions without sacrificing Reynolds number capability. The extent to which higher pressures could be used without unduly jeopardizing the cost, efficiency, and effectiveness of the overall ground test process is unclear, and the interaction between tunnel pressure and model design should be investigated further for both the transonic and subsonic tunnels. This investigation should take into account the considerable differences that exist

[9]NASA has established a Wind Tunnel Program Office at Lewis Research Center. This office, which reports to the NASA Administrator, is now working with industry to develop an acquisition strategy and conduct design trade studies for two new low speed and transonic wind tunnels, as recommended by the National Facilities Study. Participants in this effort include veteran wind tunnel designers, operators, and users from government and industry. If federal responsibility for development of these facilities is reassigned, then the designated successor should assume responsibility for actions assigned in this report to the Wind Tunnel Program Office.

between these two flight regimes. In particular, use of higher pressures is likely to be more feasible for subsonic wind tunnels than for transonic wind tunnels because of the differences in dynamic pressures.

c. **Including within the baseline design the ability to provide future growth in Reynolds number capability through use of higher operating pressures (up to 8 atmospheres), reduced temperatures (down to about −20°F), and/or a heavy test gas (such as SF_6).** Incorporating these capabilities into the new facilities would add significant cost. There are also technical concerns regarding wind tunnel tests using high pressure or gases such as SF_6. However, it would add only a few percent to the cost of the new facilities to plan ahead for future upgrades that would use one of these capabilities. For example, initially designing the Low Speed Wind Tunnel pressure shell to withstand 8 atmospheres would facilitate subsequent facility upgrades to higher operating pressures. Experience with existing facilities shows that test requirements often evolve beyond the expectations of the original designers. Failure to initially build in growth capability would make future facility upgrades highly unlikely and limit the ability of future facility operators and users to enhance tunnel capabilities. (Appendix D provides more information on how pressure, temperature, and test gas impact wind tunnel performance capabilities.)

d. **Improving the robustness of the tunnel designs.** Designing selected sub-systems and components of the new wind tunnels with margin for growth relative to pressure and operating power could improve system reliability, increase facility lifetime, and reduce the costs of future upgrades.

In addition, the Wind Tunnel Program Office should ensure that the new transonic and low speed facilities will be able to adequately support development of supersonic aircraft. The importance of low speed and transonic wind tunnels extends beyond their application to subsonic and transonic aircraft. They will also be of special importance to supersonic aircraft such as high speed civil transports that must also operate in lower speed regimes during take-off, acceleration, transonic flight over land, and landing. The design of the proposed new wind tunnels should be compatible with the test requirements of higher speed aircraft to the extent that this additional capability is affordable and does not unacceptably degrade the tunnels' ability to execute their primary mission. The detailed design phase of the new wind tunnels should also ensure that features necessary to adequately accommodate development testing of military aircraft, including stores separation testing, are incorporated into the design of the new wind tunnels as appropriate. Ongoing efforts by the U.S. Air Force to more closely define military requirements for future development wind tunnels will assist in this effort.

7. NASA and the Department of Defense should continue support for facility research in the subsonic and transonic regimes. The highest priority need in the area of low speed and transonic facilities is for new development facilities. Related research, which includes both vehicle- and facility-oriented efforts, is also important to long-term competitiveness. For example, the ability to construct practical development test facilities that use heavy gas (such as SF6) and/or very high operating pressures (15 atmospheres or more) would (1) greatly reduce facility size and cost and (2) increase Reynolds number test capability. Continued funding of appropriate research is an essential precursor to the development of future generations of ground test facilities and future upgrades of existing and planned facilities.

8. NASA and the Department of Defense should expand coordinated efforts that involve aerodynamic test facilities, computational methods, and flight test capabilities. Computational methods such as computational fluid dynamics are used during the aircraft design process to analyze and predict aerodynamic characteristics in all speed regimes. However, they must be validated by experimental ground and flight tests before they can be relied upon for design or evaluation in any phase of development.

Improved aerodynamic wind tunnel testing will provide a better understanding of aircraft fluid dynamics, including Reynolds number and boundary layer effects. This understanding will permit more-accurate scaling of ground test data to in-flight performance. Nonetheless, for the foreseeable future, computational methods will not eliminate the need for highly capable wind tunnels to support development of advanced aircraft. Continued work to improve computational methods and continued flight exploration (e.g., X-planes) *are required adjuncts* to the acquisition of new and improved wind tunnels. Better scaling methodologies are needed as soon as possible. They will be useful during the interim before new tunnels are available, and, in the long run, they will extend the utility of new tunnels for the design of very large and unusually configured future aircraft.

9. NASA and the Department of Defense should develop a continuing mechanism for long-term planning of aeronautical test and evaluation facilities. Assigning the responsibility to study future requirements and conduct long-range planning to a permanently established body would provide greater continuity than the current process of relying on intermittent, ad hoc committees. Experience with current facilities indicates that the service life of major new facilities could easily extend to the middle of the next century. The *long-term* utility of major new facilities will be greatly enhanced if their designs are based on a broad view of future test requirements.

An overall assessment of Volume II of the NFS report and a complete list of the ASEB's findings and recommendations appear in Chapter 7.

1

U.S. Response to Changing Facility Requirements

INTRODUCTION

Ever since the Wright brothers built their own wind tunnel to design their historic aircraft, ground test facilities have played a critical role in aeronautics research and development.

The production of new aircraft starts with analytically generated designs. Models of selected design options then are tested in wind tunnels. Analytical predictions and tunnel test results are compared, and, if necessary, the analytical tools are modified, candidate designs are adjusted, and wind tunnel tests are repeated until vehicle performance meets or exceeds expectations. After hardware is manufactured and assembled, flight testing is used as the final test to validate the results of the analytical models and wind tunnel testing. Shortcomings in the design process will appear as diminished flight performance and/or increased production costs. In some cases, these shortcomings may require post-production design changes.

Ground test facilities also can accelerate the development of advanced aircraft by allowing individual testing of components and subsystems before they are integrated for advanced ground and flight test. This is important because the timeliness with which new products become operational is often critically important in both military conflicts and economic competition.

For these reasons, wind tunnels have been and will continue to be a vital part of the aircraft design and development process. Superior ground test facilities, especially wind tunnels, are essential to the development of superior aircraft.

ORIGIN OF MAJOR U.S. FACILITIES

The National Advisory Committee for Aeronautics (NACA) was established by Congress and President Woodrow Wilson in 1915 to oversee aeronautical research and apply research results to the practical problems associated with civil and military aircraft.[10] One of the first activities of NACA was to determine that (1) existing aeronautical ground facilities were insufficient to support necessary research and (2) uncertainties about how the state of the art would advance made it very difficult to specify what types of facilities to build (Hunsaker, 1956). The inadequacies of current resources and uncertainty about future requirements are, perhaps, two eternal constants of advanced scientific research and the transition of discovery into products that enhance human prosperity.

Motivated by the desire to overcome these challenges, NACA worked with the War Department to establish its first research center at Langley Field, the predecessor to NASA's Langley Research Center.[11] While building its first wind tunnel at Langley, NACA conducted research using available resources, including wind tunnels at the Massachusetts Institute of Technology, the Washington Navy Yard, and the future site of Wright Field in Dayton, Ohio. In 1921, NACA sought and received approval to build a new kind of wind tunnel—one that used compressed air to markedly improve the

[10]Six of the 12 individuals appointed to NACA were members of the National Academy of Sciences. Over the next 40 years, all of the chairmen save one were also members of the National Academy of Sciences.

[11]The National Aeronautics and Space Act of 1958 created the National Aeronautics and Space Administration (NASA) as the successor to NACA. NASA incorporated the physical assets and aeronautical missions previously assigned to NACA.

[12]See Appendix D for a discussion of wind tunnel test parameters and technologies.

validity of its test results.[12] This facility was followed, in 1927, by a Propeller Research Facility for conducting full-scale tests of propellers in simulated flight conditions. During the 1930s, NACA took advantage of depression-era prices to build a number of additional facilities. In 1939, it broke ground on what is now Ames Research Center. During 1940, as the early engagements of World War II were demonstrating the unprecedented war-fighting potential of air power, NACA established what is now Lewis Research Center as a flight propulsion laboratory (Hunsaker, 1956). Several other facilities, most notably the U.S. Air Force Arnold Engineering Development Center, were christened to support continued aeronautics research and development following the close of World War II.

HISTORICAL IMPACT OF GROUND TESTING

One of the first great advances in aeronautics that can be directly attributed to wind tunnels was the NACA cowling, which was developed during the 1920s to fit over the radial cylinders of a reciprocating air-cooled engine. The NACA cowling improved the airflow around the engine and significantly decreased the drag caused by the cylinders, increasing the effective engine output without increasing the cost, fuel consumption, or weight of the engine. This cowling design was developed in NACA's Propeller Research Tunnel.

Other test programs in the Propeller Research Tunnel showed that aircraft drag was reduced when engine nacelles for multi-engine aircraft were faired into the leading edge of the wing. Previously, multi-engine aircraft such as the Ford Tri-motor had their engines slung below the wing.

The Propeller Research Tunnel was also instrumental in demonstrating that retractable landing gear improved the performance of aircraft enough to justify the corresponding increase in vehicle weight and complexity.

During World War II, many high performance fighters experienced compressibility problems during high altitude dives that were sometimes fatal. Partly in response to this situation, several new high speed wind tunnels were built after the war at NACA research centers, universities, and the Arnold Engineering Development Center to study ways of overcoming these problems. Experimentation at these facilities enabled the design of more-advanced aircraft that could withstand the higher pressures associated with near-sonic flight.

In addition to producing improved design configurations, ground testing has also fostered the development of validated design methodologies. For example, in the early 1950s, the use of the transonic research wind tunnels at Langley Field helped experimentally verify operational wing and fuselage design analysis procedures, which facilitated the production of airplane forms with reduced drag at high speed (Hunsaker, 1956). More recently, wind tunnels also have been the primary tool used to validate advanced computational fluid dynamic design methodologies.

CURRENT SITUATION IN COMMERCIAL AVIATION

Air transportation is one of the world's sustained growth industries. Over the last 30 years, revenue passenger miles have increased an average of seven percent per year (NAE, 1993). Nonetheless, concern exists within the aeronautics industry about the apparent lack of a “uniform national strategy to encourage and accommodate the planned, healthy growth of air transportation” (NAE, 1993). Problems such as airport congestion—which can restrict growth, reduce service, and increase costs—are growing in the United States and other industrialized countries. In fact, over one-half of Europe's largest airports will have reached their capacity limits by 2000, and 22 capacity-controlled U.S. airports already experience over 20,000 hours of aircraft delays per year (NRC, 1992b).

Controlling costs is particularly important for individual corporate survival in the highly competitive aeronautics marketplace of the 1990s. Controlling costs is also important to the health of the overall industry, because if costs are too high, customers will simply choose to fly less. The availability of affordable new transport aircraft that are compatible with efficient, low-cost airline operations is essential to support industry cost-containment efforts (NAE, 1993).

Subsonic, transonic, and propulsion ground test facilities are particularly important to the development of modern commercial transports. Chapter 2 and Chapter 4 focus on the specific concerns and issues associated with these types of facilities.

ACQUIRING NEW FACILITIES

The historical record documents several different methods of acquiring major new facilities. In 1916, as NACA sought to establish its first research facility at Hampton, Virginia, it petitioned funds from the War Department, because that department was the only agency with the necessary fiscal resources (Hunsaker, 1956).

After World War II, when it became apparent that the Germans had developed unprecedented ground test facilities, General Henry H. Arnold implemented a technology transfer program that involved relocation of German test equipment and scientific personnel to the United States (Wattendorf, 1986). This strategy is rarely feasible, although an analogous process is currently underway as some organizations within Europe and the United States collaborate with the former states of the Soviet Union to learn about their progress in technical disciplines where the Soviet Union might have pushed ahead of the West.

The single most ambitious aeronautics facility development program ever conducted in this country was authorized by Public Law 415 of the 81st Congress on October 27, 1949. This legislation included Title I, the Unitary Wind Tunnel Plan Act of 1949, and Title II, the Air Engineering Development Center Act of 1949. Title I authorized the appropriation of $136 million to fully fund a joint effort by NACA and the Department of Defense to devise and implement a combined (i.e., unitary) plan for developing aeronautical facilities at various sites within the United States. These facilities were intended to complement each other in responding to the needs of the U.S. aeronautics industry as it developed increasingly complex military and civilian aircraft and missiles. Title II authorized the Secretary of the Air Force to appropriate up to $100 million to establish an air engineering development center, including the construction of selected wind tunnels as specified by the Unitary Plan. This center would ultimately be christened as the U.S. Air Force Arnold Engineering Development Center.

HISTORICAL SUMMARY

Advanced ground test facilities have enabled the design of increasingly advanced civil and military aircraft at every stage of technology from World War I until the present, and they are expected to remain a key tool as the United States evaluates future options for developing new platforms such as super jumbo commercial transports, supersonic transports, civil and military tiltrotors, advanced tactical aircraft, and hypersonic cruise vehicles with suborbital or single-stage-to-orbit capabilities. Advances in aeronautical science and engineering require relevant facilities and facility technologies to provide validation data. It is no accident that the advanced state of German aircraft engineering during World War II was accompanied by wind tunnels and engine test facilities that had no equal among the Allied nations (Wattendorf, 1986).

Both NACA, starting in 1916, and General Arnold, after World War II, demonstrated that periodic examinations of the status of facilities vis-à-vis international competition and the requirements of ongoing and anticipated experimental programs are central to establishing and maintaining a position of aeronautical leadership. Furthermore, as previous studies by the National Research Council have indicated, the availability of adequate test facilities depends upon advance planning and early action to meet future requirements (NRC, 1986, 1992a). Many of the major ground test facilities in the United States were built without specific requirements, but they led to the development of new vehicles and capabilities.

Finding 1-1: The history of aviation offers several lessons learned that are relevant to the current debate on aeronautical ground test facilities.

- The future of rapidly evolving disciplines and the types of facilities they will require are often uncertain.
- Advanced aeronautical ground test facilities go hand in hand with leadership in aeronautical design and production.
- Historical precedent exists for special appropriations that provide full government funding of major aeronautical ground test facilities that are needed by industry to conduct development testing of military and commercial products.

Recommendation 1-1: *Planning for a new generation of premier aeronautical ground test facilities should consider how the lessons learned from similar past efforts apply to the current situation.*

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2

Subsonic and Transonic Facilities

INTRODUCTION

This chapter deals with the transonic and subsonic (low speed) wind tunnel facilities that are proposed to enable the United States to continue reaping the economic, environmental, and security benefits that preeminence in aviation provides. This evaluation is based on the National Facilities Study (NFS) report; interactions between the NFS team and the Aeronautics and Space Engineering Board (ASEB) during 1993 and 1994; and many individual and group discussions, including a facilities workshop hosted by the ASEB during May 16–18, 1994 (see Appendix B).

The NFS report provides a good account of much of the study's work and the resulting conclusions. This chapter provides additional information on the scope and depth of the study and on subsidiary issues, such as how to proceed with the acquisition of new and improved wind tunnel facilities.

The aeronautics portion of the NFS report concentrates on commercial air transports. However, the NFS process also considered the needs of other segments of the aeronautics industry, including defense. Deliberations during the ASEB's facilities workshop and recently generated Air Force documentation have highlighted the benefits that high Reynolds number facilities will provide to the development of military aircraft (Gideon, 1993; Leaf, 1994; Yates, 1994). Also, Department of Defense personnel participated in the NFS and have endorsed its conclusions.

From the beginning of manned flight, wind tunnel testing has been an integral and necessary part of aircraft development. Throughout most of the growth years of the air transport industry, U.S. manufacturers had access to government wind tunnel facilities that were the best in the world. As discussed in more detail later in this chapter, timely tunnel access during competitive aircraft development programs is crucial. Since the 1930s, the availability and ready accessibility of world-class facilities have been key factors enabling U.S. manufacturers to dominate the field.

The NFS report documents that Reynolds and Mach number performance of the best subsonic and transonic development wind tunnels in the United States and Europe are now close to parity.[13] However, the average age of major U.S. tunnels is about 38 years, and many of the older U.S. wind tunnels are subject to costly maintenance and breakdown. Nonetheless, there are no adequate domestic alternatives for many older facilities. For example, during the past several years U.S. manufacturers have conducted a large amount of their low speed testing in European facilities during refurbishment of the Ames Research Center 12-foot subsonic wind tunnel.

In contrast, European industry has a new government-funded transonic facility coming on-line during 1994 that is expected to significantly outperform any transonic development facilities in the United States in terms of Reynolds number capability.

More-capable wind tunnels will facilitate improvements in aircraft performance and

[13]NASA's National Transonic Facility can test at much higher Reynolds numbers than the new European Transonic Wind Tunnel (ETW). However, the National Transonic Facility is primarily a research facility, and it has very low productivity. Although productivity enhancements are planned, the ASEB agrees with the NFS that it is not practical to transform the National Transonic Facility into a development facility such as ETW, which was designed from the beginning to serve as a development facility. ETW has features such as cooled model set-up rooms and quick-change model carts that provide it with productivity several times higher than the National Transonic Facility, even with productivity enhancements.

producibility. However, as documented by the NFS, no wind tunnel in the world meets or can be affordably modified to meet the goals that the NFS generated for development of future transport and military aircraft (see Table 2-1).[14]

Table 2-1 Proposed Capabilities of New Low Speed and Transonic Wind Tunnels

TUNNEL PARAMETER	LOW SPEED TUNNEL	TRANSONIC TUNNEL
Reynolds Number	20 million at Mach 0.3 (full span model) 35 million at Mach 0.3 (semi-span model)	28.2 million at Mach 1 (full span model)
Mach Number	0.05-0.6	0.05-1.5
Productivity	5 polars per occupancy hour*	8 polars per occupancy hour
Operating Cost	<$1,000/polar	<$2,000/polar
Operating Pressure	5 atmospheres	5 atmospheres
Total Temperature	110°F	110°F at Mach 1
Maximum Power	45 MW	300 MW
Test Section Size	20 ft × 24 ft	11 ft × 15.5 ft
Flow Quality	Low turbulence	Low turbulence
Acoustic Test Capability	Acoustic test chamber	Not applicable

*A polar is a single test run consisting of 25 data points (see Appendix D).

Source: NFS, 1994.

The NFS report examines the ground test requirements of commercial air transports, which have very high flight Reynolds numbers (in excess of 60 million for the 747). An analogous situation exists for military aircraft—flight Reynolds numbers for current aircraft are as high as 60 million for the C-5 and considerably higher for the B-2.

IMPORTANCE OF GROUND-BASED FACILITIES

Ground test facilities are important, because they allow new aircraft designs to be tested early in the development cycle, thus minimizing the time and expense of making changes after the aircraft is committed to manufacturing and flight test. As aircraft have grown in size and capability, the ability to test at or near flight conditions with current tunnels has nearly disappeared for many classes of aircraft. Extrapolated data from existing wind tunnels often contain errors associated with their inability to test at these high Reynolds numbers. Such errors have caused program delays, increased costs, and limited the performance of aircraft such as the C-141, C-5, C-17, F-111, and B-2 (Table 2-2). These problems are likely to persist until aircraft designers have access to improved facilities to validate their design analyses. The cost risks associated with technical uncertainties and potential program delays affect the initiation of future aircraft development, especially for private companies.

The importance of the proposed low speed and transonic wind tunnels extends beyond their application to subsonic and transonic aircraft. They also will be important to supersonic aircraft such as high speed civil transports. These aircraft will operate in the low speed regime during take-off,

[14]The NFS initially established a Reynolds number test capability of approximately 30 million as a goal for both the low speed and transonic wind tunnels. After assessing the impact of performance goals on facility design and cost, the NFS recommended accomplishing this goal in the low speed regime using semi-span models.

acceleration, transonic flight over land, and landing. The design of the proposed new wind tunnels should be compatible with the test requirements of higher speed aircraft to the extent that this additional capability is affordable and does not unacceptably degrade the tunnels' ability to execute their primary mission.

SCALING PARAMETERS

Key among the many physical effects that must be considered during the design and test of new aircraft are compressibility and viscous phenomena (see Appendix D). Mach number is a metric for compressibility, while Reynolds number indicates the ratio of the inertia forces to the viscous forces that the atmosphere exerts on a moving aircraft. To be absolutely certain that wind tunnel test results accurately model full-scale vehicles, ground tests should approximate the flight values of these parameters simultaneously. However, for some aircraft and flight conditions, this is prohibitively costly. To provide confidence in the test results, validated scaling techniques are required that cover the entire envelope of the test aircraft.

With nonpressurized wind tunnels, Reynolds and Mach numbers are varied simultaneously, and, for most conditions, separation of the effects of each variable on the accuracy of the test results is impossible. For unpressurized, subscale tunnels, extrapolation to flight conditions can produce unusable results. Even with a pressurized tunnel, which provides some capability to vary Reynolds and Mach numbers independently, data taken at low Reynolds numbers cannot always be extrapolated confidently to flight Reynolds numbers. For example, consider Figure 2-1 , which shows wind tunnel pitching-moment data for a Boeing commercial transport at three different flap settings as a function of Reynolds number and angle of attack.[15] Reynolds number effects on pitching-moment characteristics are small up to the stall angle of attack. However, post-stall measurements of pitching moment are not repeatable at high flap settings for various Reynolds numbers. Thus, designers would not be able to use low Reynolds number tests such as these to fully and accurately determine flight performance. Development testing in new wind tunnels with the capability to simulate flight Reynolds numbers would overcome this problem.

Table 2-2 Prediction Errors Associated with Development Testing at Low Reynolds Number

AIRCRAFT PROGRAM	AREAS OF PREDICTION ERROR
C- 141	Transonic wing shock location
	Pitching moment
	Tail loads
C-5	Drag rise with Mach number
C- 17	Range/payload
F-111	Transonic interference effects
	Airframe drag
B-2	Pitching moment
	Aerodynamic drag with weapon bay door open
	Inlet distortion characteristics

Source: J.M. Griffin, 1994.

Satisfactory post-stall performance of commercial transports is required for certification by the Federal Aviation Administration, which mandates testing of aircraft beyond their normal flight envelope. For an aircraft designer who is limited to low Reynolds number facilities, variations in test data represent uncertainties that must be compensated for by either using a more conservative (and lower performance) design or accepting additional risk. Over the long run, either approach will reduce competitiveness relative to a more accurate design approach that uses high Reynolds number ground test facilities.

All of the mechanisms associated with high Reynolds number flow are not fully understood, nor is the variation of these mechanisms with Mach number. This suggests that some important flow

[15]Boeing collected the data plotted in Figure 2-1 as part of a commercial product development program that used the Ames 12-foot Low Speed Pressure Tunnel. Reynolds number was varied by adjusting tunnel pressure.

phenomena have not yet been identified. Understanding physical mechanisms is important, because it can lead to new, more-effective analytical and test approaches, creating design innovations that significantly advance aircraft performance. Geometry, Reynolds number, Mach number, lift system configuration, and lift all interact, so extrapolating test results to other combinations of these variables is questionable. Building better ground test facilities is a cost-effective way to avoid problems in the flight testing phase and ensure that new designs will perform as expected.

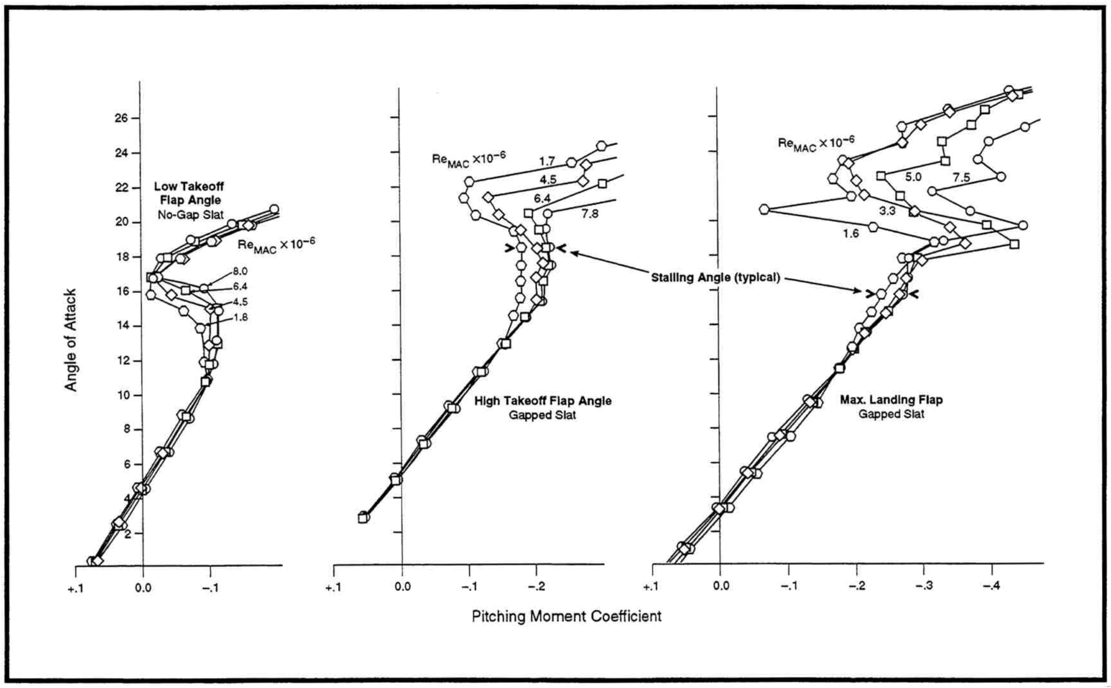

Figure 2-1 Effect of Reynolds Number on Wind Tunnel Measurements of Aircraft Pitching Moment during Take-off and Landing. Source: Boeing, 1994.

COMPUTATIONAL SIMULATION

Computational methods such as computational fluid dynamics are used during the aircraft design process to analyze and predict aerodynamic characteristics in all speed regimes. However, they must be validated by experimental ground and flight tests before they can be relied on for design or evaluation in any phase of development. Improved aerodynamic wind tunnel testing will provide better understanding of aircraft fluid dynamics, including Reynolds number and boundary layer effects. This understanding will permit more-accurate scaling of ground test data to inflight performance. Continued work to improve computational methods and continued flight exploration (e.g., X-planes) are *required adjuncts* to the acquisition of new and improved wind tunnels. Better scaling methodologies are needed as soon as possible. They will be useful during the interim before new tunnels are available, and, in the long run, they will extend the utility of new tunnels for the design of very large and unusually configured future aircraft.

TUNNEL PRESSURE AND MODEL DESIGN CONSIDERATIONS

Wind tunnel models are carefully designed to assure that their aerodynamic, structural, and dynamic characteristics meet the full-scale design intent. This requires that model surface roughness, protuberances, cut-outs, etc., faithfully represent the full-scale aircraft.

Designing new tunnels with higher operational pressures makes it possible to reduce the size of the facilities without sacrificing Reynolds number capability (see Appendix D). The realities of model design and fabrication, however, generate practical limits on the use of smaller models and elevated pressures. For a given Mach number, dynamic pressure *and* structural loading of the model increase in direct proportion to gas density and, hence, tunnel pressure. High pressures increase demands on the physical integrity of the model and the wind tunnel model support structure. This is especially significant for transonic tunnels, where full-scale dynamic pressures are already high.

For subsonic wind tunnels, model design constraints are related to the loading of high-lift system components such as flap mechanisms and tracks. Excessive dynamic pressures can cause these model components to fail or distort unless they are oversized to increase their strength. However, oversizing model parts, so that they are no longer properly scaled, causes data accuracy to become an issue. Current practice with subsonic wind tunnels has shown that design solutions are available for accurate scale models with affordable and easily workable materials up to test pressures of at least 5 atmospheres. The extent to which higher pressures could be used without unduly degrading the cost, efficiency, and effectiveness of the overall ground test process is unclear. As a result, the interaction between tunnel pressure and model design requires further investigation for both transonic and subsonic tunnels. Use of higher pressures is likely to be more feasible for subsonic wind tunnels than for transonic wind tunnels because of the differences in full-scale flight dynamic pressure.

WIND TUNNELS IN THE DEVELOPMENT PROCESS

Wind tunnel data are used to confirm or modify aircraft designs in an iterative manner until flight tests verify performance and handling characteristics. Uncertainty exists until flight tests are completed, but comprehensive ground tests at conditions that closely simulate flight conditions minimize this uncertainty. Thus, whenever possible, tunnel tests are conducted throughout the projected flight envelope of the aircraft. Many thousands of data points are recorded and analyzed for each configuration tested. A typical complete airplane development requires about 2.5 million aerodynamic simulations (Rubbert, 1994).

During the design process, computational methods produce preliminary designs that are tested in wind tunnels. Analysis of tunnel test data often results in design changes. To test the modified design, the model must be removed from the working section of the tunnel, reworked, and returned. The ability to complete the rework–retest cycle within a single shift or overnight is needed to reduce design cycle time and facilitate completion of planned testing within wind tunnel schedule constraints. To achieve fast turnaround times, the proposed new tunnels will include features such as automated controls, airlocks for quick entry, and multiple quick-change test carts with self-test systems to verify model set-up. The cost of these capabilities is significant, but it is small compared with the cost of extending the aircraft development program or encountering unexpected problems during flight test. Model turnaround time, data recording and retrieval, and other operations that impact tunnel productivity need to be quick.

Advanced aerodynamics is not the only source of improved aircraft performance. Half of the performance improvements in modern aircraft are the result of improved engines. However, superior engines will not eliminate the importance of providing improved aircraft aerodynamic configurations. Commercial jet engines are sold openly in the world marketplace, so future engine improvements will provide equal benefits to both U.S. and foreign airframe manufacturers. Without the proposed new facilities, U.S. industry will have to either indefinitely rely on the aging cadre of increasingly obsolete U.S. facilities or continue to stretch its design and development process across the Atlantic Ocean, taking advantage of the test time that European facilities make available to foreign users.

Although the highest priority need in the area of low speed and transonic facilities is for new development facilities, related research is also very important to long-term competitiveness. For example, the ability to construct practical development test facilities that use heavy gas (such as SF_6) and/or very high operating pressures (15 atmospheres or more) would (1) greatly reduce facility size and cost and (2) increase Reynolds number test capability. Continued funding of appropriate research is an essential precursor to the development of future generations of ground test facilities, and it is also likely to directly contribute to future upgrades of existing and planned facilities.

INFLUENCE OF FASTER DESIGN/TEST CYCLE

When aircraft designers prepare to introduce a new product, they must decide how far to push available technology before selecting the final design. If U.S. designers have a more efficient design-test-redesign process than their competition, they can achieve either (1) a given level of performance sooner or (2) a greater level of performance within a given period of time. Either situation, or a combination of the two, would allow U.S. products to capture a larger share of the international market than is otherwise possible, either by beating the competition to market or by introducing products with better performance.

On the other hand, if the United States is hampered by delays in its product design and development process, then economic returns will be greatly diminished even if the country ultimately produces products with capabilities equal to the competition. Inefficient design or test processes allow the competition to produce an equal or better product sooner, and there is a tremendous competitive disadvantage in arriving late to the marketplace. Many airlines standardize aircraft purchases over long periods of time to simplify maintenance and training. Thus, late introduction of a new aircraft model may permanently diminish its sales as individual airlines choose to stay with a competitors' product rather than acquire a mixed fleet of aircraft.

The high cost of developing new aircraft imposes an additional penalty. Slow design and test methodologies extend the period of time that manufacturers must fund product development, increasing the cost of bringing new products to market and reducing competitiveness.

Increasing shift hours on low-productivity facilities is not a viable strategy for competing with high productivity facilities, because the test phase of competitive aircraft design programs typically consumes every available hour of facility run time. As noted by the NFS report, development of new transport or fighter aircraft requires about 20,000–25,000 hours of wind tunnel testing (using existing facilities). Every increase in facility productivity directly reduces the number of test hours required to develop new aircraft and shortens the time to market.

U.S. aircraft manufacturers currently operate in an extremely competitive environment. Even though U.S. designers have access to European facilities, the ASEB believes that the scheduling constraints faced by U.S. users of European facilities and the inefficiency of conducting transatlantic design and development efforts inevitably delay the introduction of new products. Conversely, European competitors have greater access to better test facilities and, potentially, to the data generated when U.S. aircraft manufacturers use European wind tunnels. In combination with other improvements that the U.S. aeronautics industry is making in its design and manufacturing process, the ASEB believes that the construction of advanced development wind tunnels will be an important contribution to the productivity of that industry.

The NFS did not conduct a detailed assessment of the option of building new international facilities in which all partners would have equal access and assured protection of competition-sensitive data. However, even with such an approach, U.S. industry believes that tunnel location could still create competitive inequities. Also, it seems doubtful that the Europeans, who are preparing to open the new European Transonic Wind Tunnel (ETW), would be inclined to participate in an international venture to build another transonic development facility that would draw users away from ETW.

Because of national security concerns, foreign facilities are especially inappropriate for development of military aircraft. The U.S. defense industry is generally limited to U.S. facilities, even if more-capable facilities are available overseas. Thus, the ASEB believes it is unlikely that new or existing foreign or international facilities will be able to adequately respond to near-term requirements for subsonic and transonic development testing of commercial and military aircraft.

The ASEB concurs with the NFS report that:

- acquisition of advanced high productivity wind tunnels in the United States, where U.S. designers can efficiently coordinate their wind tunnel, model-building, and computational activities will improve the effectiveness and efficiency of the aircraft design and development process; and
- these improvements are important to the economic viability of the U.S. aeronautics profession and industry because of the vital role that design process efficiency plays in the worldwide aircraft manufacturing competition.

WIND TUNNEL DESIGN REQUIREMENTS

The proposed design of the new low speed wind tunnel enables testing of the high lift systems that define aircraft performance during take-off, climb-out, and landing. The transonic tunnel supports testing during aircraft cruise and maneuvering at velocities up to Mach 1.6. (Commercial jet transports today cruise at speeds no higher than about Mach 0.9. The capability of the transonic tunnel to support testing at higher velocities is based on military requirements. It will also be important in the development testing of high speed civil transport designs.)

Although the ASEB did not independently analyze the tunnel design parameters shown in Table 2-1, it judges that they are well developed, and their achievement is reasonably assured. Although near-flight Reynolds numbers will not be achieved for the largest of the transport aircraft designs contemplated for the next decade, the target Reynolds and Mach numbers for each of the tunnels appear to be an acceptable compromise among tunnel cost, productivity, and technical risk. For example, the Reynolds number capability of the proposed transonic wind tunnel (28 million) will be significantly less than the design Reynolds number of the new ETW (50 million). However, the proposed U.S. facility will have much higher productivity (8 polars per hour versus 1.5 for ETW). The ASEB agrees with the NFS that this is an appropriate trade, particularly because U.S. designers have the option of using the U.S. National Transonic Facility (productivity of 0.36 polars per hour at a Reynolds number of 119 million) to conduct limited verification testing at very high Reynolds numbers.

The productivity and cost goals of the proposed subsonic and transonic facilities appear to be attainable for most tunnel tests. Other tunnel requirements concerning turbulence, noise, wall boundary interference effects, simulation of jet-engine inlet and exhaust flows, and interactions of engine flows with external aerodynamic flows are acknowledged by the NFS, and the ASEB anticipates that tunnel design solutions will be further refined during the detailed design phase. The design phase also should ensure that features necessary to adequately accommodate development testing of military aircraft, including stores separation testing, are incorporated into the design of the new wind tunnels as appropriate. Ongoing efforts by the U.S. Air Force to more closely define military requirements for future development wind tunnels will assist in this effort. For example, the Air Force Materiel Command hosted a government/industry workshop on August 2-3, 1994, at Arnold Engineering Development Center to assess military requirements for development wind tunnels. Workshop participants included representatives of the Wind Tunnel Program Office.

The ASEB agrees with the NFS that building the two tunnels as proposed is likely to enable subscale development testing for more than half of the new commercial transport aircraft projected for the next 20 years or so at flight Reynolds and Mach numbers. In particular, the new wind tunnels would allow testing models of existing aircraft such as the B-737 and MD-90 at flight Reynolds number. This is likely to significantly improve the correlation of wind tunnel and flight data for future designs of conventional aircraft that have flight Reynolds numbers beyond the test limit of the proposed tunnels. However, the flight Reynolds numbers of (1) very large commercial transports, (2) high speed civil transports, (3) high performance military aircraft, and (4) some revolutionary design concepts that might emerge in the future would exceed the capabilities of the proposed tunnels. Thus, the test results for these aircraft would have to be extrapolated to analyze their performance at flight Reynolds number. Nonetheless, this process would generally be more accurate than extrapolations based on data obtained from the less capable tunnels now available.

During the tunnel design phase, additional tunnel configurations should be considered to evaluate lower cost alternatives such as:

- making relatively small increases in tunnel operating pressure (increasing pressure by 10 percent—to 5.5 atmospheres—could reduce facility cross-section size requirements and the cost of facility construction on the order of 20 percent);[16] and
- building a single tunnel with both low speed and transonic test capabilities.

The extent to which performance and operational costs would be compromised by building a single, dual-use facility should be evaluated in terms of reduced acquisition costs. Joint utilization of control facilities or airflow and power components for both subsonic and transonic testing may also be feasible. However, like the option of building a single tunnel for subsonic and transonic testing, this would reduce total available test hours and the ability of new facilities to satisfy utilization rates projected by the NFS. These utilization rates, which appear to be reasonable, should be verified as part of the proposed assessment of using a single facility for both subsonic and transonic testing.

As previously stated, the ASEB agrees that the proposed Reynolds number capabilities for the low speed and transonic wind tunnels seem appropriate. However, given the long lifetime of major wind tunnels, it would be prudent to consider how future facility operators and users might wish to enhance the proposed new facilities. Experience with existing facilities shows that test requirements often evolve beyond the expectations of the original designers. Facility upgrades are unlikely to be cost-effective unless the baseline design anticipates the need for future modifications and makes allowances for them. Therefore, the ASEB recommends conducting design trade studies to evaluate possible future upgrades to the Reynolds number capabilities of the proposed tunnels. These assessments should take into account the differences in tunnel and model parameters (such as dynamic pressure) between the subsonic and transonic wind tunnels.

The design trade studies should specifically assess the relative merits of operating each of the proposed tunnels (1) at increased pressure (up to 8 atmospheres), (2) at reduced temperatures (down to about −20°F), and (3) with heavy gas. Testing with

[16]For a given Reynolds number capability, increasing design pressure by 10 percent allows an equivalent reduction in the maximum characteristic length a wind tunnel must accommodate. This allows reduction of the cross-sectional area of the wind tunnel test section by about 20 percent. Thus, to the first order, a 10 percent increase in pressure could reduce a wind tunnel's overall size and cost by about 20 percent.

heavy gases increases Reynolds number in much the same way as increased pressure, although the use of a test gas other than air raises questions about the validity of test data.[17] Incorporating these capabilities into the new facilities would add significant cost. There are also technical concerns regarding wind tunnel tests using high pressure or gases such as SF_6. However, it would add only a few percent to the cost of the new facilities to plan ahead for future upgrades that would use one of these capabilities. For example, initially designing the Low Speed Wind Tunnel pressure shell to withstand 8 atmospheres would facilitate subsequent facility upgrades from 5 atmospheres to higher operating pressures. Failure to initially build in growth capability would make future facility upgrades highly unlikely and limit the ability of these facilities to meet new ground test requirements.

Tunnel wear out and breakdown have been problems with some key existing facilities, primarily because of their age. The 12-foot subsonic wind tunnel at Ames Research Center is still a critical part of the U.S. facilities infrastructure even though it was built in 1946. Accordingly, attention should be given to the selection of simple and robust tunnel designs, including appropriate materials, for the proposed new facilities. Designing selected subsystems and components with margin for growth relative to pressure and operating power could improve component reliability, increase facility lifetime, and reduce the costs of future upgrades.

PRELIMINARY DESIGN AND COSTS

NASA and the Department of Defense formed the Facilities Study Office (FSO) to support the NFS Task Group on Aeronautical R&D Facilities. One of the FSO's major tasks was to assess the costs, schedule, and technical merit of alternative concepts for new subsonic and transonic wind tunnels under consideration by the NFS. The work of the FSO is documented in Volume II-A of the NFS report.

The FSO prepared bottom-up comparative cost estimates for wind tunnel conceptual designs using a five-tier work breakdown structure. First, the FSO generated an initial engineering estimate of the cost of fabricating each work breakdown structure element. It then estimated the cost risk and design cost of each element. Cost risk accounted for uncertainties associated with design requirements, item complexity, design maturity, and site conditions. The average value of cost risk assigned was 24 percent. The total cost of each element of the work breakdown structure was formed by adding the engineering estimate, cost risk, and design cost. The NFS summed these costs for every element of the work breakdown structure to calculate the estimated construction cost. The FSO then estimated the project's total cost by adding the cost of (1) contractor profit; (2) bonding; (3) inflation during the construction process; (4) supervision, inspection, and engineering services; (5) preliminary and final system design; (6) government project management; and (7) a contingency equal to 10 percent of the estimated construction cost. For the NFS' preferred design, these last seven factors accounted for 47 percent of the project's total estimated cost.

The conceptual designs and accompanying cost estimates that this process generated appear to be well done. The cost estimates are especially thorough considering the early stage of the project. Nevertheless, pending the completion of a preliminary engineering report and formal design study, the ASEB surmises that these estimates remain subject to the usual range of uncertainties. The engineering design, bidding, and construction process should focus on cost containment as well as technical goals. The current budget environment makes it essential to prevent cost growth, even if this requires sacrificing some initial capabilities and deferring them to future upgrades.

The NFS report estimates that it would cost $3.2 billion and take 10 years to construct the proposed new wind tunnels using standard federal procurement procedures. It also reports that “nonstandard

[17]When the test gas is not air, the test data must be interpreted to account for the impact of differences in the specific heat constant.

(i.e. commercial like) acquisition and concurrent design and construction practices" could reduce cost and schedule to $2.55 billion and eight years. Although the NFS report characterizes the $2.55 billion, eight-year cost and schedule estimates as conservative, the ASEB cautions against further reductions in planned cost and schedule estimates unless they are justified by specific changes in the design or acquisition approach. The ASEB believes that the biggest risk faced by major projects such as this relate to the unexpected. Thus, that portion of the cost estimate that is attributable to cost risk and contingency planning should be carefully conserved to deal with unexpected problems that may arise.

ECONOMIC AND ENVIRONMENTAL FACTORS

The ASEB agrees with the NFS that development of the proposed high Reynolds number subsonic and transonic wind tunnels can provide economic benefits through:

- competitive advantages associated with significant improvements in aircraft maximum lift capability and cruise efficiency, which are sensitive to Reynolds number effects;
- reduced aircraft operating cost and structural weight;
- higher payload and range;
- increased sales of commercial transports and improved market share; and
- higher gross domestic product, a more positive trade balance, and increased domestic employment.

Table 2-3 illustrates the performance gains that might be obtained by projected improvements in new aircraft (Boeing, 1994). The new high Reynolds number wind tunnels would facilitate the achievement of these gains by better simulating flight conditions during take-off, landing, and cruise.[18] The maximum take-off weight, engine static thrust at sea level, fuel burn per seat at 2,000 nautical miles, and direct operating cost for two classes of airplanes are shown. Comparisons of these parameters illustrate the marked potential advantage of aircraft developed with the proposed new tunnels. Particularly impressive is the projected reduction of 18.9 to 22.2 percent in fuel burn. This improvement would provide a direct reduction in the engine emissions, environmental impact, and operational costs of new commercial aircraft.

The NFS report uses data taken from the Boeing Commercial Group's 1993 Current Market Outlook to project a potential transport aircraft market of $815 billion for the period between 1992 and 2010. The report also uses industry sources to estimate the economic benefits of the proposed new facilities. It estimates that the proposed new facilities would improve airplane cruise and take-off and landing performance by at least 10 percent each. Performance improvements are essential for the U.S. aeronautics industry to maintain or increase market share. Based on the information available to it, the ASEB considers these projected increases in performance to be potentially attainable and believes that the proposed facilities could substantially facilitate such improvements.

These forecast advantages do not include the probable operating and development cost reductions that would accrue to future U.S. military aircraft programs. In addition to direct cost reductions, access to improved ground test facilities would make advanced military aircraft more competitive in the world market, thereby further reducing the defense burden carried by U.S. taxpayers. Foreign sales of U.S. military aircraft result in lower unit costs for U.S. government and foreign purchasers.

Starting development of the proposed new tunnels as soon as possible will

[18]The benefits shown in Table 2-3 include contributions from both proposed tunnels. The low speed wind tunnel would contribute to improvements in the design of high lift systems for take-off and landing. A new transonic wind tunnel would impact aircraft cruise performance. The National Facilities Study report concluded that cruise performance has greater leverage on aircraft operating costs than take-off and landing performance. The ASEB agrees with this assessment.

maximize their economic payoff. There is an immediate need for the competitive advantages they offer, and their payoff will accrue far into the future.

Table 2-3 Illustration of Potential Improvements in Aircraft Performance.

	AIRCRAFT TYPE			
PARAMETER	BASE QUAD	IMPROVED QUAD	BASE TWIN	IMPROVED TWIN
Maximum Take-off Weight (lb)	1,240,000	1,113,000	534,800	480,600
Sea Level Static Thrust (lb)	73,500	56,300	73,500	53,200
Fuel Burn/Seat at 2,000 nm (lb)	162.1	131.5 (−18.9%)	168.2	130.9 (−22.2%)
Direct Operating Cost (¢/seat-mile)	1.372	1.189 (−13.3%)	1.391	1.196 (−14.0%)
Assumptions: Quad airplane represents a potential new, very large commercial transport. Twin airplane represents a 777-equivalent design. Increases in M=0.03; Cruise L/D=4%; Takeoff L/D=6%; C_{Lmax}=15%				

Source: Boeing, 1994

Over the last 25 years, as European aeronautics technology has risen to equal U.S. technology, the U.S. market share in transport aircraft has declined by 30 percent. Although market share is a function of many different factors, if other nations achieve a higher level of aeronautical technology, erosion of the U.S. market share may accelerate, with accompanying reductions in balance of trade and jobs. Continued advances in aerodynamic technology are necessary to avoid this situation. The proposed facilities represent an investment that is only a small fraction of the potential future gain and will provide an opportunity to enhance U.S. technology development.

Although the precise size of the future transport aircraft market is uncertain, it is sure to be quite large. Projected annual sales for 2010 are $60 billion (in 1993 dollars), and between 25 and 35 percent of the total projected market is accounted for just by replacement of existing aircraft (McDonnell Douglas, 1992; Boeing, 1993). Consequently, investing in the resources necessary to maintain U.S. competitiveness is in the best interest of the country. However, the decision to build the high Reynolds number subsonic and transonic tunnels must balance the need for more-capable facilities with specific performance parameters, the costs of building and operating new facilities, and the economic benefits that are likely to result. Based on the analyses conducted by the NFS, other factors discussed in this chapter, and the benefits that the United States could derive from the tunnels in terms of balance of trade, employment, and economic activity, the ASEB recommends proceeding with the design and development of new subsonic and transonic facilities while more fully exploring the items recommended herein for further study.

Finding 2-1. With regard to low speed and transonic facilities, the findings of the Aeronautics and Space Engineering Board are as follows:

a. Significant aerodynamic performance improvements are achievable, and the nation that excels in the development of these improvements has the opportunity to lead in the global market for commercial and military aircraft.

b. New high-Reynolds-number ground test facilities are needed for development testing in both the low speed and transonic regimes to assure the competitiveness of future commercial and military aircraft produced in the United States. These facilities will also contribute to the development testing of supersonic aircraft, such as high speed civil transports, by characterizing flight characteristics during takeoff, acceleration, transonic flight over land, and landing.

c. Facility configuration trade-off studies conducted by the NFS on Reynolds number, productivity, and life cycle cost appear to be sound. Additional configuration studies are needed for both the subsonic and transonic tunnels. Each assessment should take into account the differences in tunnel and model parameters between subsonic and transonic wind tunnel testing. These additional assessments should cover the following topics:

(1) using a single tunnel to test both the low speed and transonic speed regimes;
(2) making incremental changes to tunnel operating pressures (e.g., from 5 to 5.5 atmospheres) to allow reduction of facility size and cost without sacrificing Reynolds number capability;
(3) including within the baseline design the ability to provide future growth in Reynolds number capability through use of higher operating pressures (up to 8 atmospheres), reduced temperatures (down to about −20°F), and/or a heavy test gas (such as SF_6); and
(4) improving the robustness of the tunnel designs by designing facility components with margin for growth in pressure and operating power to improve component reliability, increase facility lifetime, and facilitate future upgrades.

d. Completion of planned upgrades to existing facilities is an essential complement to the acquisition of new facilities.

e. Facility research on high pressure wind tunnels and other wind tunnel concepts should continue. These efforts should include research related to high pressure wind tunnel models.

f. Scaling methods are essential to current design processes. Even with new facilities, scaling of ground test results will still be necessary to accommodate full-scale simulation of very large or innovative aircraft designs that may be developed in the future. Coordinated efforts to develop improved scaling methods that use wind tunnel testing, computational methods, and flight tests should be expanded.

g. New facilities offer potential benefits to the U.S. economy and the global environment that are large compared with the investments required.

Recommendation 2-1. *The ASEB recommends the following:*

a. NASA's Wind Tunnel Program Office should proceed with the design and development of new subsonic and transonic facilities while conducting the four design trade studies noted in Finding 2-1.c during the design phase of the wind tunnel program. It should also ensure that the detailed designs of the proposed new wind tunnels will adequately support requirements related to factors such as noise, turbulence, simulation of jet-engine flows, low speed testing of supersonic aircraft, and testing of military aircraft and systems.

b. NASA should complete planned upgrades to existing facilities as soon as possible.

c. NASA and the Department of Defense should continue facility research on high pressure wind tunnels and other concepts.

d. NASA and the Department of Defense should expand efforts to develop advanced scaling methods that involve wind tunnel testing, computational methods, and flight tests.

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3

Supersonic Facilities

INTRODUCTION

The supersonic flight regime, which is generally considered to include velocities up to Mach 5, is relevant to military aircraft, missiles, and supersonic transports. Although the current demand for supersonic testing is relatively small compared with the demand for subsonic and transonic testing, supersonic test capabilities are an important part of the overall ground test infrastructure. The reduced level of demand, however, creates special problems, because scarce resources tend to migrate to more active facilities. Nonetheless, the Department of Defense will have continuing needs for supersonic ground testing of new and upgraded military flight vehicles and systems, and NASA's High Speed Civil Transport Program will create additional demands for access to supersonic wind tunnels.

PRIOR STUDIES

Many studies of aeronautical ground test facilities during the last few years have included supersonic facilities within their scope. The results of five major efforts are summarized in Tables 3-1a and 3-1b. They indicate that there are essentially two areas of special interest regarding the future of supersonic facilities: (1) maintaining and upgrading supersonic testing at the 16S facility at Arnold Engineering Development Center, and (2) developing a new low-disturbance (or “quiet”) facility to investigate supersonic boundary layer transition, mixing, and turbulent boundary layers, with the goal of achieving supersonic laminar flow control. Laminar flow technology would greatly reduce the drag and surface temperature of new supersonic aircraft designs and enhance the economic performance of a high speed civil transport. However, the five studies are divided over which option to pursue. The 1992 report *Future Aerospace Ground Test Facility Requirements for the Arnold Engineering Development Center* recommends investing in the center's existing 16S facility (NRC, 1992b). It does not advocate building a new low-disturbance facility, though it does recommend that the 16S upgrade plan consider the need for improved flow quality and laminar flow testing. Three of the reports focus primarily or exclusively on NASA facilities, and they all recommend building a new quiet supersonic wind tunnel.

THE CHALLENGE

The 16S facility at Arnold Engineering Development Center has proven its capability to support the development of advanced supersonic military aircraft and missiles. A high speed civil transport, because of its larger size, will have a higher Reynolds number requirement. Nonetheless, NASA's High Speed Civil Transport Program plans to develop a first generation aircraft by using a combination of ground testing at existing facilities (primarily the 16S supersonic tunnel at Arnold Engineering Development Center) and flight testing. Thus, the challenge faced by the 16S facility concerns primarily (1) counteracting the effects of age to maintain its capabilities and (2) using available new technology to update selected performance capabilities. The most significant maintenance action anticipated concerns the common 16S/16T drive system, which would take over three years and several hundred million dollars to completely replace. Past studies have also recommended considering technology upgrades for the 16S facility to, for example, increase productivity by installing advanced computer systems, reduce airflow turbulence and noise, and provide for supersonic laminar flow testing (NRC, 1992b).

Table 3-1a Recent Studies of Supersonic Ground Test Facilities

Future Aerospace Ground Test Facility Requirements for the Arnold Engineering Development Center (NRC, 1992b)

- Focus: Military requirements for new and improved facilities for ground testing and computational modelling at Arnold Engineering Development Center
- Recommendation (relevant to supersonic facilities): Arnold Engineering Development Center should plan for long-term maintenance and upgrading of the 16S tunnel, its premier supersonic test facility, which is now over 40 years old.
- Cost: No estimate provided

Industry/DoD/NASA Workshop on Aerodynamics/Aerothermodynamics/Acoustics Ground and Flight Testing Requirements (NASA, 1992)

- Ad hoc group of about 75 individuals from government, industry, and academia hosted by NASA Langley Research Center, July 23–24, 1992
- Focus: Major research and production-oriented ground and flight test facilities for industry, DoD, and NASA
- Recommendation: (relevant to supersonic ground test facilities): The U.S. should acquire a new quiet (low disturbance) supersonic (Mach number 1.6–2.6) tunnel by 2000.
- Cost: No estimate provided

Building an aircraft with supersonic laminar flow characteristics would significantly reduce its drag and surface heating and increase its fuel efficiency. However, designing a cost-effective supersonic laminar flow facility to conduct development testing is complicated by interactions between the various structures within supersonic wind tunnels. For example, noise created by turbulent boundary layers on wind tunnel walls directly affects the stability of model boundary layers. The solution to this complex problem is likely to require a continued program of theoretical and experimental investigation. Each of the prior studies summarized in Table 3-1a and Table 3-1b recommends acquiring the capability to conduct supersonic laminar flow wind tunnel testing. However, these studies indicate that there is some diversity of opinion regarding how best to achieve that goal.

NATIONAL FACILITIES STUDY SUPERSONIC FACILITY REQUIREMENTS

The NFS benchmarked the capabilities of U.S. and foreign supersonic wind tunnels, evaluating over 40 different facilities. It focused on facilities with flight-like Reynolds numbers and Mach numbers in the range of 2.0 to 5.0.

The study noted that the primary users of supersonic test facilities have been the Department of Defense and military aircraft manufacturers, although NASA's High Speed Civil Transport Program, if successful, will generate a need for the civil aircraft industry to conduct extensive supersonic testing of large aircraft with cruise speeds between Mach numbers 2.0 and 2.4.

Having reviewed the requirements of the Department of Defense and the High Speed Civil Transport Program, the NFS Task Group on Aeronautical R&D Facilities concluded that existing test facilities such as 16S were essentially adequate to meet future needs. It recommended investing $42 million in 16S, including $24 million for drive-system upgrades. The balance would fund additional reliability upgrades, productivity improvements, and other work consistent with previous studies.

The ASEB endorses the proposed investment in upgrading the common 16S/16T drive-system and urges further consideration of additional activities to improve the reliability of the drive system motors and compressors. The actions recommended by the NFS include modifications to existing motors that should significantly enhance their reliability. Nonetheless, in case of failure, major motor repairs could take from four months (to rewind a motor stator) to over three years (for complete motor replacement). Although Arnold Engineering Development Center estimates that motor problems requiring complete replacement are very unlikely, credible accidents such an electrical arc-over with severe internal motor damage could reduce the operational capability of 16S (and 16T) for up to a year (Laster, 1994). This would have a severe impact if it occurred at a critical point in an aircraft development program. Additional drive-system improvements should be carefully considered to reduce the probability of such an occurrence.

Compressors are also critically important to the health of the 16S/16T facility complex. A 16T compressor failure once took that facility out of service for four years, and a 16S compressor failure took nearly six years to repair. Arnold Engineering Development Center, however, has greatly reduced the expected severity of future compressor failures by replacing steel compressor rotor blades with plastic blades, and motor upgrades now seem to be more urgent than compressor improvements (Laster, 1994).

Although the NFS acknowledges the importance of laminar flow technology for supersonic aircraft such as a high speed civil transport, it concludes that (1) upgrading 16S to provide this capability is not practical and (2) improvements in nozzle design and fabrication technologies are needed to build a new facility with levels of tunnel turbulence low enough to conduct desired laminar flow testing. Thus, the NFS recommends addressing this area by (1) using existing ground and flight test facilities to develop a first-generation high speed civil transport, (2) allocating $12 million to conduct research and development on how to construct a quiet supersonic tunnel operating at Mach numbers between 2.0 and 2.4 (the anticipated cruise velocity for a high speed

Table 3-1b Recent Studies of Supersonic Ground Test Facilities

Aeronautical Technologies for the Twenty-First Century (NRC, 1992a)

- Focus: High-leverage technologies for advancing commercial aeronautics
- Recommendation (relevant to supersonic wind tunnels): NASA should study the means to develop a supersonic, low-disturbance test capability at full-scale Reynolds numbers of 400–500 million and Mach 2–6.
- Cost: No estimate provided

Review of Aeronautical Wind Tunnel Facilities (NRC, 1988)

- Focus: Military and civil requirements for wind tunnels and the ability of existing facilities, especially NASA wind tunnels, to meet them.
- Recommendation (relevant to supersonic wind tunnels): NASA should use existing technology to acquire a small (nozzle size of 20 × 30 inches) low-disturbance supersonic wind tunnel with a Mach number of 3.5 and the ability to accept additional nozzles to generate Mach numbers of 2.5–6
- Cost: No estimate provided

Assessment of NASA's Major Wind Tunnel Facilities with Respect to Current and Future National Needs (NASA, 1987)

- Ad hoc group of retired NASA, industry and DoD personnel, August 1987
- Focus: Military and civil requirements for wind tunnels and the ability of existing NASA facilities to meet them.
- Recommendations (relevant to supersonic wind tunnels): Same as the 1988 NRC Review of Aeronautical Wind Tunnel Facilities (see above)
- Cost: $5 million for single Mach number capability of 3.5

civil transport) to support the development of subsequent generations of high speed civil transports, and (3) evaluating the use of a flying laboratory such as a Tu-144, the Russian supersonic transport, as a near-term supplement to ground testing. Currently, supersonic laminar flow control is being evaluated on the NASA F-16 XL aircraft.

Finding 3-1: U.S. supersonic wind tunnels adequately satisfy most current and potential test requirements. Shortfalls exist in productivity, reliability, maintainability, and laminar flow test capabilities.

Recommendation 3-1: The Aeronautics and Space Engineering Board recommends upgrading the 16S facility at Arnold Engineering Development Center to include continued improvements in the 16S/16T motor drive and compressor systems. Research to define test requirements and develop practical facility concepts for supersonic laminar flow technology should be continued.

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4

Propulsion Facilities

INTRODUCTION

Turbopropulsion test facilities within the United States have the capability to test current air breathing engines under the operating conditions experienced during take-off, climb, cruise at flight speeds up to Mach 3.8, approach, and landing. Looking to the future over the next 10 to 30 years, air breathing engine test facility requirements will be determined by engine size, type, configuration, and air flow requirements. As facility modifications usually take several years of planning and four to eight years of construction, it is important to accurately project future needs.

The ASEB expects that an increase in air flow capability for the Aeropropulsion Systems Test Facility at Arnold Engineering and Development Center will be required for the next generation of high-bypass subsonic engines during the next seven to 12 years. To accommodate large supersonic cruise engines (sea-level air flow of 1,000 pounds per second or more) such as those needed for high speed civil transports, the altitude flight envelop of the Aeropropulsion Systems Test Facility could be expanded from 45,000 to 60,000 feet with the addition of an ejector at the engine exhaust. Arnold Engineering Development Center estimates the cost of such a modification to be about $200,000. NASA and industry are currently working to solve both economic and technical barrier problems associated with the development of high speed civil transports in order to position industry to launch a development program in the next eight to 15 years.

FACILITY OVERVIEW

Air breathing propulsion facilities can be broken down into four major categories:

1. *Propulsion wind tunnels.* Propulsion wind tunnels, which permit free-jet testing of the engine and nacelle are primarily very large government-owned facilities, such as the 40-foot × 80-foot and 80-foot × 120-foot tunnels at NASA's Ames Research Center. Usually, atmospheric pressure and temperature conditions exist in these wind tunnels. Air flow and Mach number are used to simulate take-off and landing conditions, including thrust reverse.
2. *Altitude engine test facilities.* Major altitude engine direct-connect facilities are owned by both government agencies and industry.[19] In these facilities, engines are run in an environment that duplicates the full envelope of flight conditions. Two of the new-generation large high-bypass engines for the Boeing 777 aircraft are being altitude tested at Arnold Engineering Development Center to avoid the capital investment required to upgrade industry owned facilities.
3. *Sea-level engine test facilities.* Sea-level engine test facilities are primarily industry-owned. They are used to both develop and verify performance, including cross-wind inlet distortion effects, noise, emissions, and durability.
4. *Engine component test facilities.* Component test facilities in government, industry, and academia are used to develop, improve, and gain insight into the behavior of various parts of the engine under a controlled environment. Component testing facilitates the “building block” approach for development by getting key components ready prior to full-up engine testing.

[19]Free-jet facilities allow engine installation in test sections similar to conventional wind tunnels. Some of the air flow enters the engine, and the rest of the test facility air flow passes around the outside of the engine. In a direct-connect facility, the engine intake is directly connected to the source of test air, and all of the air flow passes through the engine.

These four facility types cover the full range of demonstration requirements to develop commercial and military aircraft engines.

ENGINE DEVELOPMENT

The Integrated High Performance Turbine Engine Technology program, sponsored by the Department of Defense, is the key U.S. initiative and rallying point for improving the performance and affordability of military aircraft engines. In addition, the transfer of technology developed by this program to the U.S. commercial markets plays a vital role in civilian aeronautics and the balance of trade. Improving the performance of the core engine (gas generator) is the key to developing improved air breathing engines for both military and commercial applications.

Figure 4-1 shows the relationship between specific core engine gas power and turbine rotor inlet temperature, illustrating that improved performance is indeed possible. Core power is normalized by mass flow, so both large and small engines can be represented. During the past 50 years, as turbine temperatures have increased, specific core power has grown by a factor of five over the early jet engines of Frank Whittle and Hans von Ohain. Demonstrator engines have operated successfully at eight times the power of these early engines.

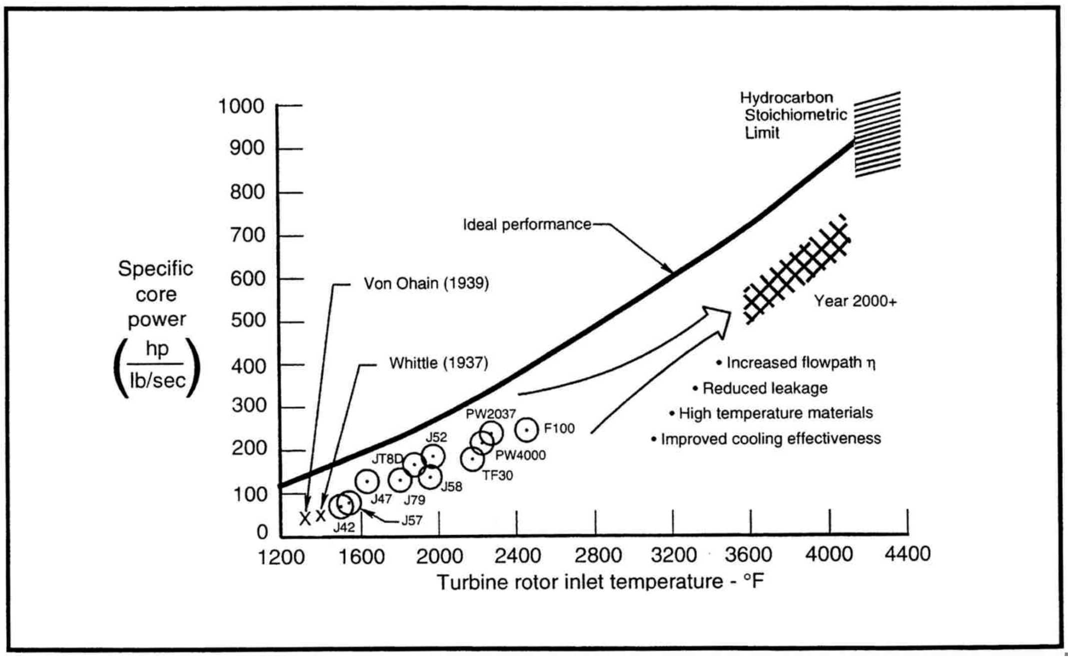


Figure 4-1 Improving Core Performance of Turbopropulsion Systems. Source: Koff, 1991.

The ideal Brayton cycle performance shown in Figure 4-1 represents 100 percent component efficiencies and no cooling air. Theoretical performance is truncated at the fuel stoichiometric limit (fuel/air ratio = 0.068) at which all oxygen and fuel are consumed. The theoretical limit on core power is almost 20 times higher than the power of early turbojets and four times higher than the power of current engines in production. Given that actual engine power will be lower than the ideal, industry expects that a concentrated technology effort could achieve an increase in core power of 2.5 over current production engines within the next 20 years.

The trend toward higher specific core engine power through technology advances is the key to the configuration design of fighters, military transports, strategic aircraft, and commercial aircraft, because they all use technologically similar core engines to develop the gas power for their propulsion systems.

Air breathing engines fall into three basic flight regimes: subsonic, supersonic, and hypersonic. These are discussed in the following subsections.

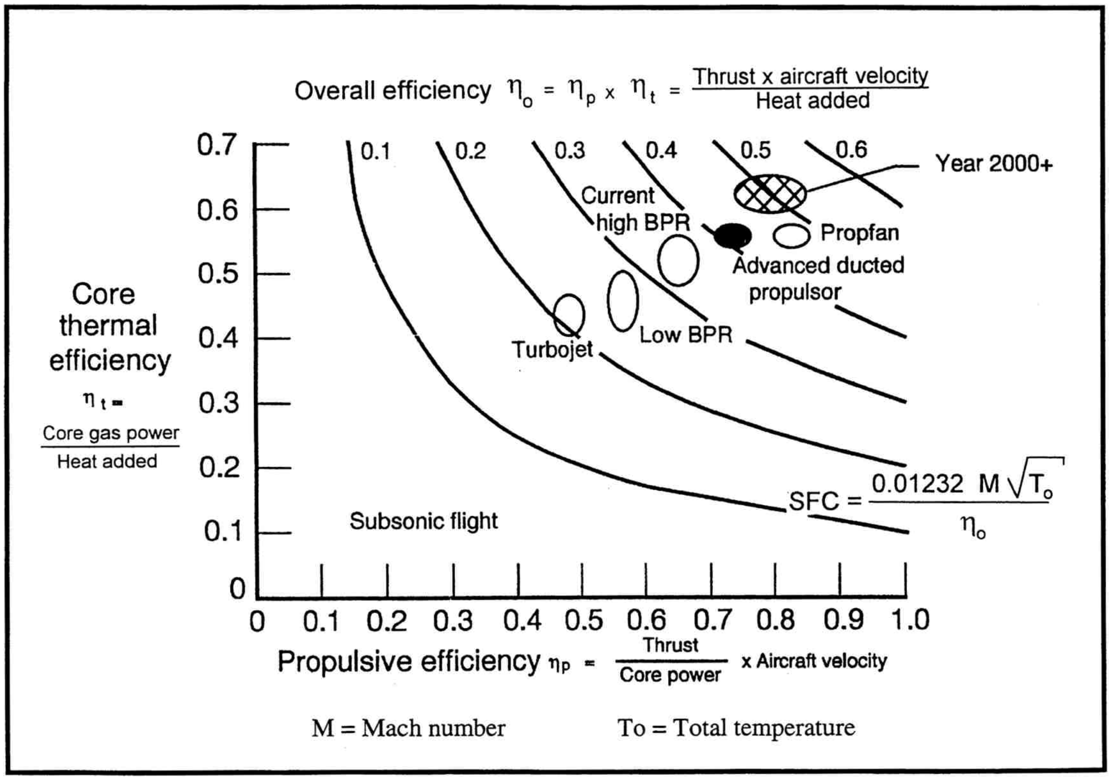


Figure 4-2 Trends in Overall Efficiency of Subsonic Turbopropulsion Systems Indicating a Target Goal in 2000 + for High Efficiency. Source: Koff, 1991.

Subsonic Commercial and Military Transport Engine Development

The "final frontier" in conventional subsonic propulsion is represented by the cross-hatched region in Figure 4-2. Industry is developing three basic types of engines to reach this goal for commercial passenger, heavy cargo, and military transport applications:

- high bypass ratio (five to nine) direct-drive turbofans that produce up to about 90,000 pounds of thrust;
- gear-drive turbofans (some with reversing pitch blades for thrust reverse) that produce up to about 120,000 pounds of thrust and use

slim-line nacelles to minimize interference drag with the wing-pylon installation; and

- ultra-high bypass ratio (40 to 60) unducted propulsors that use reversing pitch blades for thrust reverse (the thrust produced by these engines is dependent on application).

For bypass engines (also referred to as turbofans, as opposed to turbojets, which have zero engine bypass), the nacelle air flow is split into two separate streams. The outer (bypass) stream flows through the fan, while the inner stream flows to the core engine, which produces the engine's power. The ratio of the fan bypass flow to the core engine flow is defined as the engine bypass ratio. At constant core engine power, fan bypass pressure ratios are reduced to accommodate high engine bypass ratios, and this lowers the velocity of the jet exhaust. For subsonic flight, lower jet velocity is desirable, because it reduces jet noise and improves propulsive efficiency, which decreases specific fuel consumption (SFC).

Higher thermal efficiency (η_t) and propulsive efficiency (η_p) result in higher overall efficiency (η_o), which is the product of η_t and η_p. Commercial engine developers use higher compression pressure ratios and higher turbine temperatures to increase core power and thermal efficiency, and they use higher bypass ratios and lower jet velocities to increase propulsive efficiency and reduce noise.

The advanced core engine technologies required to increase performance as projected in Figure 4-1 are being actively pursued with both industry and government funding. To reach the goals shown in Figure 4-2, significant technological advances are also required for the large propulsor, which includes the fan (fixed or variable pitch), gear drive, and nacelle. Progress in moving from the best of current engines to further-improved higher bypass engines (η_o>0.40) depends on the ability of the propulsion industry to make the required investment.

Supersonic Commercial Engine Development

NASA's High Speed Research program is working to overcome technical barriers (noise, emissions, and economics) associated with the development of a supersonic commercial transport. This program will develop the advanced technologies required for a high speed civil transport, which is currently projected to operate at Mach 2.0– 2.4 and an altitude of 55,000–60,000 feet. Arnold Engineering Development Center is already positioned to play a key role in meeting the propulsion test requirements for this effort. Ejector/diffuser incorporation into the center's Aeropropulsion Systems Test Facility will provide the required altitude simulation capability.

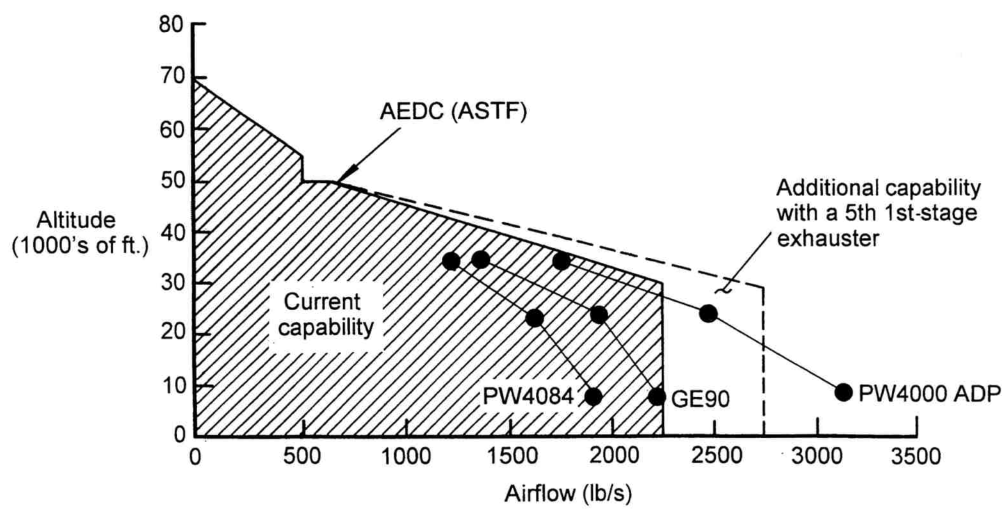
Military Engine Development: Subsonic, Supersonic, and Hypersonic

Military engine technology is concentrating on:

- low observables (radar and infrared);
- vectoring nozzles (pitch and yaw);
- direct lift coupled with lift fans;
- higher thrust-to-weight ratio;
- supersonic cruise using higher-energy core engines to drive higher fan pressure ratios; and
- production of derivative engines by using the technology base to decrease development and production costs.

Military airlift engine programs will most probably adapt advanced commercial engines to provide increased range and payload.

During the past 10 years, most hypersonic technology funding has focused on the Mach 0 to 25 National Aero-Space Plane program. A significant redirection of this program is in progress. Studies are continuing to define Mach 3 to 5 air breathing engines for hypersonic applications, which may be needed in the twenty-first century. The 1989 report of the Air Force Scientific Advisory Board report identified the “wind tunnel in the sky" (i.e., a research aircraft) as the only "test facility" for high Mach (8 to 15) flight. Work is still in progress to identify realistic and practical methods of ground testing air breathing supersonic combustion ramjet (scramjet) engines beyond Mach 7.



PW4084: Turbofan with a 112-inch diameter fan and a bypass ratio of 7 to 1. It was recently certified for Boeing 777 aircraft.
GE90: Turbofan with a 123-inch diameter fan and a bypass ratio of 9 to 1. It is being developed for the Boeing 777 aircraft.
PW4000 ADP: Advanced ducted propulsor with a geared PW4000 core, a bypass ratio of at least 12 to 1, low noise, and thrust of at least 100,000 pounds. It is a candidate design for potential future large aircraft.

Figure 4-3 Comparison of Exhauster Capability of the Aeropropulsion Systems Test Facility and New Bypass Engines. Source of data: Pratt & Whitney, General Electric, and Arnold Engineering Development Center.

For the future, propulsion fuel sources other than petroleum-derived fuels will undergo intensive investigation. These initiatives may require special facilities, and major national facility planning efforts need to stay current. The nuclear propulsion option, as an example, could become a practical reality sometime during the next 30 to 50 years.

PROPULSION FACILITY REQUIREMENTS

Figure 4-3 shows that the current Aeropropulsion System Test Facility at Arnold Engineering Development Center is adequate for altitude testing of the newest generation of high-bypass engines, such as the PW4084 and GE90. However, a 40 percent increase in flow capacity might be required to handle the next generation of ultra-high-bypass, gear-driven propulsor engines such as the PW4000 Advanced Ducted Propulsor (ADP). These engines could be certified after the year 2000—if the aircraft manufacturers develop new, larger aircraft that require such engines. A Pratt &

Whitney geared-fan ADP demonstrator engine in the 50,000 pound thrust class that uses a medium-size PW2037 core was tested in 1993 at the Pratt & Whitney West Palm Beach ground test facility and at the 40-foot × 80-foot free jet wind tunnel at NASA's Ames Research Center. The advanced ducted propulsor engine shown in Figure 4-3 represents a geared 12 to 1 bypass ratio configuration that uses the larger PW4000 core engine.

The nature and timing of upgrades to the Aeropropulsion Systems Test Facility are heavily dependent on the launch of a new large aircraft requiring engines with significantly higher air flow. Implementation of facility upgrades for these larger subsonic engines would take four to eight years, so there is time to "wait and see" before deciding how to proceed. The addition of another exhaust compressor, at a cost of approximately $50 million, would increase the air flow capability of the Aeropropulsion Systems Test Facility to 2,750 pounds per second, as shown. This would fill part of the altitude test gap for future generations of subsonic high bypass engines. Arnold Engineering Development Center has identified other upgrades to the Aeropropulsion Systems Test Facility that would be needed to provide air flow up to 3,500 pounds per second. Cost estimates for these upgrades are on the order of $500 million.

Finding 4-1. Current propulsion facilities in the United States are world class and adequate to meet current and near-term test requirements.

Recommendation 4-1. *Communication between the government agencies that operate national aeropropulsion facilities and industry should be continued to assure propulsion facility readiness relative to future requirements. In particular, the ASEB concurs that the study proposed by the NFS should be conducted.*

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5

Hypersonic Facilities

INTRODUCTION

Most hypersonic test facilities in the United States were built in the 1950s and 1960s to support development of intercontinental ballistic missiles, the space program, and research into first-generation hypersonic vehicles such as the X-15. Although many of these facilities have been used during the past two decades to support the space program, several were mothballed or even dismantled in the 1970s. Thus, current U.S. hypersonic test capabilities consist primarily of older test facilities, many of which are in serious need of refurbishment, and a few newer facilities that were built to support the National Aero-Space Plane.

Termination of the National Aero-Space Plane at the end of fiscal year 1994 places the immediate future of hypersonic vehicle development in jeopardy. If the United States wishes to retain its capability to develop future hypersonic aircraft, spacecraft, missiles, and planetary probes, adequate facilities will be needed. The National Research Council noted in a 1989 study that ground test facilities did not exist to support complete testing of scramjet engines (NRC, 1989). Development of such facilities normally takes 10 years, and it is unlikely they could be available if not started before a new development program is underway. The National Aero-Space Plane program encountered this difficulty when it needed additional facilities for testing engines and cryogenic tanks (Richey, 1993).

In summary, significant deficiencies must be addressed if the United States is going to maintain a vigorous hypersonic program into the next century. Areas such as low noise and turbulence levels and real-gas effects need to be accurately simulated for flight greater than Mach 8.

PRIOR STUDIES

As shown in Table 5-1a and Table 5-1b, hypersonic ground test facilities have been examined as part of several major studies during the last few years, and the conclusions of these studies are consistent. They generally agree on the following points:

1. More-capable hypersonic ground test facilities are needed to adequately support future development programs.
2. State-of-the-art technology is not adequate to build major new hypersonic facilities that will have the desired capabilities in areas such as model size, run time, pressure, temperature, and velocity.
3. Near-term efforts should focus on a program of research to select, develop, and demonstrate the most promising hypersonic test facility concepts.
4. Long-term efforts to build hypersonic development facilities will be contingent on successful completion of the near-term facility research effort and concurrent efforts to validate future requirements for hypersonic vehicles.

THE CHALLENGE

The airframe and propulsion systems of hypersonic vehicles must meet aerodynamic and aerothermal requirements over a wide speed regime, from Mach 5 to Mach 25. Understanding the hypersonic flight environment and how to simulate it in a ground test facility is difficult. Vehicle development requires close simulation of the full conditions of flight. Adequate test-section size and test duration are essential for reliable test results. Numerical simulation is highly dependent upon the accurate modeling of these types of flows. An incomplete understanding of boundary layer transition; combustion; and high temperature, real-gas effects could cause serious computational errors, particularly at high Mach numbers (above Mach 8). Because of these limitations, a full understanding of the performance of hypersonic vehicles is highly unlikely without additional research involving ground tests, flight tests, and computational modeling (USAF Scientific Advisory Board, 1989).

Table 5-1a Recent Studies of Hypersonic Ground Test Facilities

Future Aerospace Ground Test Facility Requirements for the Arnold Engineering Development Center (NRC, 1992)

- Focus: Military requirements for new and improved facilities for ground testing and computational modelling at Arnold Engineering Development Center
- Recommendation (relevant to hypersonic facilities): Develop a road map to institute a two-phase program by building a high quality Mach 8 facility accompanied by a hypersonic facility research effort. Phase Two would build on the results of Phase One by building a major hypersonics development facility.
- Cost: No estimate provided

Hypersonic Test Investment Plan (HTIP Working Group, 1993)

- Ad hoc committee of personnel from government; industry, and academia; established by DoD and NASA, December 1992
- Focus: Civil and military requirements for new and improved facilities for ground testing and computational modelling
- Recommendation: Institute a long-term program supporting facility research, pilot facilities, instrumentation, test methodologies and computational science.
- Cost: About $35 million per year during the first 10 years

NATIONAL FACILITIES STUDY HYPERSONIC FACILITY REQUIREMENTS

The Hypersonics Working Group of the NFS Task Group on Aeronautical R&D Facilities reviewed the historical record relating to hypersonic ground test facilities. It evaluated both U.S. and foreign hypersonic test facilities, many of which were built over two decades ago in support of the space program. These facilities were placed into one of three groups:

1. aerodynamic/aerothermodynamic facilities;
2. aeropropulsion facilities (including internal combustion); and
3. structural/airframe test facilities.

As a result of these reviews, the Hypersonics Working Group determined that U.S. national facilities are inadequate for future systems development, particularly for propulsion and real-gas testing above Mach 8. Foreign hypersonic facilities, which are better than domestic facilities in limited areas, also were not considered adequate.

As part of its study, the Hypersonics Working Group considered how computational fluid dynamics (CFD) and flight tests help to define ground test facility requirements. Although CFD modeling has made impressive progress, the validity of CFD results are highly dependent upon the accurate modeling of various flow fields, including complex dissociated and combustion-type flows. Since these kinds of flows are still not fully understood, serious computational errors are likely to occur, particularly at high Mach numbers (above Mach 8). Thus, calculations must be validated using ground-based facilities or flight experiments. Because of the limitations associated with CFD verification, complete hypersonic performance evaluation may only be achieved through flight test over the vehicle's entire speed regime.

Based on these findings, the NFS recommended starting a two-phased construction and facility refurbishment program. Phase I would focus on facility research to explore new approaches to hypersonic testing, while Phase II would provide the needed systems certification facilities for vehicle development. Three low-risk facilities would be built as part of Phase I to help meet current needs for hypersonic ground testing. In addition, the Phase I effort would include a time-phased development program to study facility concepts for more-complex facilities that are beyond the current state of the art. These facilities would be constructed in Phase II, when the necessary technology is available. The estimated cost to carry out these recommendations is about $220 million to build the initial facilities, plus $20 million per year for the facility research effort. These recommendations are consistent with the results of the other studies summarized in Table 5-1a and Table 5-1b.

Finding 5-1: The National Facilities Study report is consistent with prior studies of hypersonic test capabilities.

Recommendation 5-1: *To address the hypersonic ground test deficiencies identified in previous studies, the ASEB endorses the objectives of the two-phase program recommended in the National Facilities Study report.*

Table 5-1b Recent Studies of Hypersonic Ground Test Facilities

Hypersonic Technology for Military Application (NRC, 1989)

- Focus: Military applications for hypersonic aircraft and the technologies related to such vehicles
- Recommendations (relevant to ground test facilities):

- –Consider building a quiet tunnel for Mach 10 testing at close to full-scale conditions
- –Consider building a facility for testing components at temperatures above the 1200°C limit of available facilities

- Cost: No estimate provided

Requirements for Hypersonic Test Facilities (USAF Scientific Advisory Board, 1989)

- Focus: Civil and military requirements for new and improved facilities for computational modelling, ground testing, and flight testing
- Recommendations (relevant to ground test facilities):

- –Initiate a research program to support eventual construction of a large national hypersonic ground test facility, then
- –Proceed with a national facility, if it is justified by a broad-based requirement for a full-scale engineering development capability

- Cost: $138 million for facility construction and upgrades, plus $20 million per year to support facility research

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6

Additional Considerations and Future Directions

INTRODUCTION

Beyond the central topic of what aeronautical ground test facilities the United States will need in the future, some additional considerations bear mentioning. For example, the terms of reference for the NFS note the importance of policy issues regarding possible joint funding of new facilities by government and industry, shared usage of facilities, and facility management and operation. The ASEB recognizes the importance and potential impact of nontechnical issues on the overall process of upgrading U.S. ground test facility capabilities. Accordingly, this chapter focuses on selected issues of this type.

PRICING POLICY AND FACILITY USAGE

The NFS report recommends establishing a pricing policy for development testing that would charge domestic users of new wind tunnels for both direct and indirect costs. The report asserts that this pricing policy will maximize effective use of new wind tunnels. Additionally, the NFS recommends charging foreign users higher fees that include capitalization costs, presumably to allow international customers to share in paying for the capital costs of these facilities.

The NFS emphasizes the importance of operating costs by making them one of the three key parameters used to characterize the proposed new low speed and transonic wind tunnels. The ASEB agrees that operating cost is an important characteristic of any facility involved in the development of commercial products, because facility usage is likely to be a strong function of user costs in a highly competitive business such as the commercial aeronautics industry.

A comparison of operating cost goals and the amortized cost of construction shows that user fees will grow significantly if they include the amortized cost of construction. As shown by Table 6-1, the wind tunnel cost and performance goals established by the NFS Task Group on Aeronautical R&D Facilities result in anticipated hourly operating costs of $5,000 and $16,000 for the low speed and transonic wind tunnels, respectively. Depending on the assumed usage, the amortized cost of construction varies from as little as $3,600 per occupancy hour per facility for a 40-year facility lifetime—if no interest charges are included—to as much as $19,300 per occupancy hour—if interest on capitalization costs are computed at an annual interest rate of six percent. Including these costs in the pricing structure could greatly increase user fees, thereby counteracting the benefit of building new facilities with lower operational costs.[20]

The ASEB takes no position on what pricing policy should govern the use of particular ground test facilities. However, changes in pricing policy should be carefully considered to avoid invalidating the assumptions upon which estimates of future facility usage are based. This is especially

[20]This analysis assumes that the two proposed wind tunnels can be constructed using commercial business practices for $2.55 billion. The National Facilities Study estimates that standard government procurement procedures would result in an acquisition cost of $3.2 billion, which would correspondingly increase the amortized cost of construction.

true for large facilities such as the proposed subsonic and transonic wind tunnels that are designed to accommodate a particular level of operational use.

Table 6-1 Comparison of Wind Tunnel Operating and Capitalization Costs

WIND TUNNEL OPERATING COST GOALS		
	Low Speed Wind Tunnel	**Transonic Wind Tunnel**
Polars per hour*	5	8
Operating cost (per polar)	$1,000	$2,000
Operating cost (per hour)	$5,000	$16,000
*A polar is a single test run consisting of 25 data points.		
AMORTIZED COST OF CONSTRUCTING EACH FACILITY		
(Single facility cost of $1.275 billion amortized over 40 years)		
	Principal Only	Principal plus Interest (6% APR)
100% Duty	$32 million/year	$85 million/year
Cycle	$3,600/occupancy hour	$9,700/occupancy hour
65% Duty	$32 million/year	$85 million/year
Cycle	$5,600/occupancy hour	$14,900/occupancy hour
50% Duty	$32 million/year	$85 million/year
Cycle	$7,300/occupancy hour	$19,300/occupancy hour

Finding 6-1: Pricing policy can have a significant impact on user fees. The size of user fees, in turn, is likely to influence user demand, which is an important factor in planning the construction of new facilities.

Recommendation 6-1: *The government should make pricing policy an integral part of the decision-making process that it uses for major new ground test facilities. The government should carefully consider any subsequent changes in pricing policy to ensure that they do not compromise the economic viability of its facilities.*

FACILITY MANAGEMENT

The NFS report identifies several options for managing new wind tunnels—by NASA, jointly by NASA and the Department of Defense, or by a consortium involving industry and government—but it does not recommend a particular course of action.[21] The U.S. aeronautics industry frequently conducts test programs using NASA and Department of Defense wind tunnels. Historically, Department of Defense facilities are inclined to be more production-oriented. The design of NASA facilities, on the other hand, has tended to emphasize research capabilities over productivity (NRC, 1988).

The NFS report recommends taking immediate action to reduce the projected cost ($2.55 billion) and schedule (eight years) of acquiring new low speed and transonic wind tunnels. The ASEB agrees that reducing cost and schedule is an important goal, but it cautions against using management-directed cost and schedule estimates to provide the illusion of achieving this goal.

The management structure that the federal government establishes to implement and

[21]The cost estimates prepared by the Task Group on Aeronautical R&D Facilities (see Volume IIA of the task group's final report) assume that final design and construction of the proposed low speed and transonic wind tunnels are completed by a single prime contractor.

oversee the acquisition of new facilities has the potential to be a determining factor regarding the ultimate success of those efforts. For example, joint agency programs that require multiyear appropriations will suffer if changes in personnel, departmental priorities, or other factors over the course of time cause sponsoring agencies to change their expectations and priorities in ways that destroy the consensus upon which the program was founded. If one partner unilaterally decides to reduce its financial contribution, it can place the entire investment at risk. This risk is heightened with long-term, high-value programs, because there is more time for consensus to break down, and the fiscal pressures are larger.

The importance of establishing an effective and efficient management approach is amplified by the prospect of shared funding and usage of facilities between government and industry. Industry members that help pay for facility construction are likely to demand a special relationship in formulating pricing and usage policies.

Finding 6-2: Management structure, including agency sponsorship, can materially impact the ability of large acquisition programs to meet their cost and schedule goals. Management structures that feature oversight or sponsorship by multiple agencies or organizations tend to increase schedule and cost risk, especially for expensive, long-term programs.

Recommendation 6-2: *The government should select a facility management structure that minimizes cost, schedule, and programmatic risk.*

ACQUISITION STRATEGY

In developing its baseline cost and schedule estimates for constructing new low speed and transonic wind tunnels, the NFS Task Group on Aeronautical R&D Facilities assumed that the tunnels would be built using normal government procurement practices. As noted in the previous section, the task group recommends taking immediate action to reduce the cost and schedule of these facilities, and it identified the use of commercial acquisition practices as one way to achieve this goal. The ASEB agrees that federal procurement practices tend to increase cost and schedule requirements. Using a government/industry consortium to construct these facilities with a combination of federal and commercial business practices is one way to address this issue.[22]

The NFS report identifies three options for funding the construction of the proposed subsonic and transonic wind tunnels: industry only; a government/industry consortium; and government only. After assessing these options, the NFS "envisioned that the facilities will be constructed primarily with government funding," and it concluded that "funding by industry alone is not a viable source of capitalization." However, it also determined that the possibility of obtaining funding jointly from government and industry "could not be ruled out" and it recommended conducting "further studies to look at innovative funding approaches and government/industry consortia arrangements." The ASEB agrees that this area deserves further study.

Finding 6-3: Construction of new facilities using an acquisition process unimpaired by the full weight of federal acquisition regulations would reduce cost and schedule requirements.

Recommendation 6-3: *The proposed low speed and transonic wind tunnels should be acquired using the most efficient combination of federal and commercial acquisition practices.*

[22]NASA and several members of the U.S. aeronautics industry have formed such a team to develop and evaluate preliminary designs for the proposed tunnels.

SITE SELECTION

The Facility Study Office[23] identified site selection as a "critical problem area that must be resolved as soon as possible" (NFS, 1994). It noted that site selection influences both acquisition and operating costs, and that site selection should be completed prior to preliminary design review to avoid unnecessary cost growth or schedule delays.

In January 1989, after the Department of Energy selected Dallas/Fort Worth as the preferred site for the superconducting super collider, the General Accounting Office (GAO) evaluated the site selection process (GAO, 1989). The super collider, like the proposed new wind tunnel facilities, was highly coveted because of the economic stimulus that its construction and operation would provide to the community in which it would be located. The GAO made a single recommendation in its report: advocates of specific sites should be provided with as much information as possible regarding evaluation criteria in order to allow them to make a more informed decision on whether to prepare a formal site proposal. The Wind Tunnel Program Office should ensure that its site selection process follows this recommendation.

Attachment seven to Volume II-A of the NFS report responds to this recommendation by listing and describing numerous evaluation factors, such as available transportation, electric power, natural gas, water, weather, existing infrastructure, site conditions, work force availability, the nature of the local community, and environmental factors.[24] Evaluation factors are grouped in 11 areas, which are weighted to show their relative importance.

In addition to the GAO report referenced above, the GAO produced two additional reports in 1989 in response to congressional concerns about the super collider site selection process. These reports concluded that the Department of Energy —which used a National Research Council committee to identify a short list of best-qualified sites—seemed to have acted properly in evaluating the proposed sites.

Finding 6-4: For facilities such as the proposed low speed and transonic wind tunnels, which will require large technical staffs and huge amounts of energy, selection of a less-than-optimum site will degrade the efficiency and increase the cost of facility construction and operation, particularly if power availability restricts wind tunnel operating hours.

Recommendation 6-4: *If a decision is made to build the proposed tunnels, the site selection process should proceed in a timely fashion. In order to optimize the cost-effectiveness of the proposed new wind tunnels, the process should focus on objective criteria—such as those contained in Volume II-A of the NFS final report—that are directly related to the mission of the proposed facilities.*

OVERALL PRIORITIES

Volume II of the NFS report concludes that "the largest and most critical need is for new high Reynolds number, high productivity subsonic and transonic wind tunnels." The ASEB concurs that these wind tunnels should be the next development facilities built, because they will enhance the competitiveness of the U.S. transport aircraft industry, whose health is essential to the future of aeronautics in the United States. Economic survival of the air transport manufacturers is mandatory for the United States to preserve the industrial base necessary to maintain a large positive balance of trade in aeronautics and to carry out future

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[23]The Facility Study Office was a separate organization consisting of personnel from NASA and the Department of Defense that worked together at Langley Research Center from May through December 1993. It supported the NFS Task Group on Aeronautical R&D Facilities by providing detailed financial and technical assessments of selected low speed and transonic wind tunnel design options.

[24]If industrial partners are involved in managing facility acquisition, they are likely to request inclusion of additional factors, such as proximity to their primary manufacturing sites. For example, when the Boeing Corporation recently contemplated private construction of new wind tunnel facilities, it required potential sites to be accessible by air travel from its facilities in Seattle, Washington, in six hours or less.

programs in both aeronautics and space. These facilities are also important to meeting Department of Defense needs for future military aircraft (Yates, 1994; Leaf, 1994; Gideon, 1993).

Construction of new supersonic, hypersonic, or propulsion development facilities is not a current priority. Additional research is needed before undertaking construction of suitable next-generation supersonic and hypersonic development facilities (see Chapter 3 and Chapter 5). There is also no immediate imperative to start work on new aeropropulsion development facilities pending better definition of future requirements (see Chapter 4).

Regarding the relative importance of the subsonic and transonic wind tunnels, the ASEB agrees with the government and industry participants in the NFS that the transonic facility is of greatest importance. The NFS report concluded that improvements in aircraft cruise performance, which would result from testing in a new transonic wind tunnel, have greater leverage on aircraft operating costs than high lift performance during take-off and climb, which is tied to low speed wind tunnel testing. This encourages a development sequence for the two tunnels that favors the transonic tunnel.

In addition, a new U.S. transonic facility is needed to adequately respond to the challenge raised by the new ETW (European Transonic Wind Tunnel). As discussed in Chapter 2, no U.S. facility can effectively compete with ETW as a development facility.

On the other hand, the pending recommissioning of the 12-foot low speed tunnel at NASA's Ames Research Center, which has a Reynolds number capability of 10 million, will provide U.S. manufacturers with an interim alternative to continued use of European low speed facilities. Nonetheless, the U.S. needs a new high-productivity, high-Reynolds-number (30 million) subsonic wind tunnel as soon as possible. Such a facility will enable U.S. industry to advance the state of the art of aircraft design and position itself to compete effectively for future sales of commercial transport aircraft, which are projected to exceed one trillion dollars over the next 20–25 years.

Implementing the key recommendations of the NFS report in the supersonic, hypersonic, and propulsion areas would cost significantly less than the cost of building the proposed subsonic and transonic facilities. Thus, the decision whether to execute those recommendations need not be tied to the decision-making process for the new development facilities. Instead, the merit of the proposed supersonic and hypersonic facility research should be compared with the benefit of other potential research efforts under consideration by NASA and the Department of Defense. They should be funded as part of a comprehensive effort to advance supersonic and hypersonic vehicle design and test capabilities. The same is true for subsonic and transonic facility research, which the NFS report does not address, but which the ASEB believes is important to the long-term viability of development testing in these speed regimes.

Historically, about half of the gains in aircraft performance have been the result of improved propulsion systems. Accordingly, the ASEB unequivocally recommends conducting the proposed study of propulsion test facility requirements. The minimal cost of this activity far outweighs the potential penalty of failing to properly project future needs in this area.

The ASEB concurs with the recommendations of the NFS regarding facility consolidation and closure. The proposed actions seem to be a prudent compromise between the competing objectives of maintaining overall test capabilities and reducing overhead costs associated with the existing ground test infrastructure.

Recommendation 6-5: *The ASEB recommends acquisition of new transonic and subsonic wind tunnels as the number one priority in the area of development wind tunnels. If both facilities are not acquired in parallel, then the transonic facility should lead the subsonic facility. Research related to subsonic, transonic, supersonic, and hypersonic facilities should be prioritized and executed as coordinated efforts that involve other related research programs conducted by NASA and the Department of Defense. A study of future propulsion facility* *requirements should be pursued independently of these other activities.*

SCOPE OF CURRENT STUDIES

Development of advanced aircraft is a complex, iterative process. A wide variety of disciplines must come together synergistically if the final product is going to rank best in the world. However, the NFS Task Group on Aeronautical R&D Facilities did not evaluate all types of aeronautical research and development facilities. Rather, it focused on ground-based aerodynamic and aeropropulsion facilities in order to accommodate limitations on time and resources. Thus, the NFS report says little or nothing about the possible need for advanced, more-capable vertical flow spin tunnels, rotorcraft whirl towers, facility instrumentation technologies, computational facilities, structural test facilities, sonic fatigue test facilities, temperature and vibration test facilities, system operational test facilities, flight and cockpit simulators, or flight test facilities. Similarly, this National Research Council report does not analyze requirements for these types of facilities. However, this does not imply that the ASEB has determined that the types of facilities not addressed are adequate. In fact, the references cited in this report specifically recommend taking action to correct shortcomings in many areas not examined by the NFS. Nonetheless, the kinds of facilities mentioned above are not discussed in this report because they are outside the study scope that was agreed upon by NASA and the National Research Council.

Finding 6-6: The National Facilities Study and this National Research Council study have not analyzed requirements for many types of important aeronautical test facilities, such as vertical flow spin tunnels, rotorcraft whirl towers, computational facilities, and flight test facilities.

Recommendation 6-6: *The results of the National Facilities Study and this National Research Council study should not be used to assert that types of facilities that were outside the scope of their deliberations are unimportant to the future of the U.S. aeronautics industry, even though such facilities are not discussed in the resulting reports. The work of the NFS Task Group on Aeronautical R&D Facilities should be augmented to develop a comprehensive view of future requirements for aeronautical ground test facilities. Furthermore, any effort to develop new wind tunnels should be structured to take maximum advantage of the synergy that exists between ongoing advances in the technologies associated with ground, flight, and computational facilities.*

INTEGRATED TEST AND EVALUATION METHODOLOGIES

Aircraft manufacturers are working to reduce the acquisition and ownership costs of state-of-the-art aircraft. One way to achieve this objective is to reduce the time it takes to design new products and bring them to market. Another is to achieve performance goals with more-producible, lower-cost designs. Accordingly, industry is more fully integrating its test and evaluation methodologies to combine simulation methodologies (i.e., computational methods, ground testing, and flight testing) with development processes for the airframe, engines, and other individual aircraft systems.

This integration applies throughout the acquisition cycle, from concept development through production, deployment, and operational support. For example, multidisciplinary computational modeling of aerodynamics, structures, and heat transfer processes early in the development process can enable the use of joint, simultaneous testing of aerodynamics (using wind tunnels) and engine performance (using propulsion test facilities). This combination can accurately predict the full-scale flight performance of each engine-airframe design combination under consideration (Kraft, 1993).

Integrated test and evaluation can also improve overall aircraft performance by showing designers how individual component design changes impact the entire vehicle. By more fully accounting for the interactions between aircraft systems, this process facilitates the design of systems that optimize aircraft producibility and performance. Integrated design methodologies may only produce subtle design changes, but in a highly competitive environment such as aeronautics, performance gains and lower production costs are important competitive advantages.

Finding 6-7: Judicious use of more-effective test and evaluation methodologies can maximize the impact of new and upgraded facilities on the competitiveness of the aeronautics industry.

Recommendation 6-7: *Facility development efforts should ensure that new and improved physical assets are designed to accommodate foreseeable advances in test methodologies and other disciplines that will affect facility effectiveness. This will require coordinating advances in ground test capabilities with planned improvements in computational and flight test capabilities.*

AERONAUTICAL FACILITY LONG-RANGE PLANNING ISSUES

This document and the referenced reports describe many challenges faced by the U.S. aeronautics industry and why both new and upgraded ground test facilities are needed to adequately address them. However, the effort to satisfy these requirements should not overlook other nontechnical issues that are also essential to the future success of the domestic aeronautics industry. Although these issues are often complex and not easily solved, their resolution is generally not contingent upon large allocations of fiscal resources. The following examples are taken from previous studies of aeronautical ground test facilities.

- *Advanced Planning.* The highest priority recommendation of the report *Aircraft and Engine Development Testing* (NRC, 1986) concerned the need for “a policy incorporating advanced planning and early funding commitments for testing and test facility preparation.” The National Research Council actually considered this policy issue to be more pressing than the technical shortcomings of available facilities. The report's number three recommendation emphasized this point by calling for annual reviews of current and projected facility weaknesses relative to the requirements of vehicle development programs.

Six years later, a different unit of the National Research Council formed a committee that included none of the participants in the 1986 study.[25] This new study evaluated the ground test facilities at Arnold Engineering Development Center. The first recommendation of the report produced by this study also focused on the need for long range planning (NRC, 1992).

The need for more-effective planning was further emphasized by an Aeronautics Advisory Committee report on NASA's aeronautical facilities. Five of its seven recommendations discussed ways to improve facility planning, including development of a “rolling ten-year plan, updated annually” (NASA, 1991). The ASEB strongly agrees with the importance of taking the long view in planning major new facilities. Experience with current facilities indicates that the service life of major new facilities could easily extend to the middle of the next century. The long-term utility of major new facilities will be greatly enhanced if their designs are based on a broad view of future test requirements.

- *Facility Utilization.* The National Research Council has determined that pricing policies governing the use of federally-owned facilities can impede the ability of military and

[25] *Aircraft and Engine Development Testing* was authored by a committee of the NRC's Air Force Studies Board. The 1992 report on facilities at Arnold Engineering Development Center was authored by a committee of the Aeronautics and Space Engineering Board.

industry customers to effectively use those facilities (NRC, 1992).

- *Funding Policy for Facility Construction.* In its 1991 report, the NASA Aeronautics Advisory Committee concluded that NASA's process for construction of facilities was too inflexible, particularly with regard to the provision of adequate funding for preliminary engineering reports and design work associated with complex research facilities. Failure to adequately fund such activities unnecessarily reduces the accuracy of preliminary cost estimates and project schedules (NASA, 1991).
- *Facility Maintenance Standards.* The first problems identified by the report *Review of Aeronautical Wind Tunnel Facilities* (NRC, 1988) concern NASA's failure to establish and live up to "common experience-based standards for the maintenance and improvement of major experimental facilities" and the lack of a timely process to authorize critical, unexpected facility repairs. The National Research Council's 1992 report on facilities at Arnold Engineering Development Center confirmed that failure to fund a minimal level of maintenance and repair was a continuing problem.

Finding 6-8: The service life of major new facilities could easily extend to the middle of the next century. Furthermore, the need for long-range planning of facility needs is a recurrent theme in past studies of aeronautical ground test facilities. Assigning the responsibility to study future requirements and conduct long-range planning to a permanently established body would provide greater continuity than the current process of relying on intermittent, ad hoc committees. Delegating this responsibility to an existing body could achieve the desired goal without adding to the number of government advisory panels.

Recommendation 6-8: *Long-range planning of future requirements for national aeronautical ground test facilities should be carried out on a continuing basis by a permanently established body such as an interagency advisory group or standing committee. The designated body should work with relevant government agencies and industrial groups to resolve policy and procedural issues that diminish the effectiveness of current and future facilities.*

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7

Summary

OVERALL ASSESSMENT OF VOLUME II OF THE NATIONAL FACILITIES STUDY REPORT

Volume II of the NFS report is the result of an impressive team effort by numerous personnel from government and industry. Although the report appears to be complete within its guidelines, it does not provide a detailed technical evaluation and analysis of the work that supported the aeronautics portion of the NFS. The conclusions and recommendations of the NFS seem to be supported by factual material wherever it was available, although in some cases they are based on the best judgement of the study participants.

The federal agencies involved in the NFS approved the study terms of reference (see Appendix A and Appendix C). Early deliberations by the NFS Task Group on Aeronautical R&D Facilities resulted in a decision to focus on ground test facilities related to aerodynamic and propulsion testing. As a result, the NFS did not investigate specific requirements in areas such as flight testing, computational facilities, vertical flow spin tunnels, facility instrumentation technologies, or structural test facilities. As discussed in Chapter 6, the ASEB recommends augmenting the NFS to develop a more comprehensive view of future requirements for all aeronautical test facilities. In addition, the NFS report mentions very little about military needs for new facilities, although participants in the NFS and a recent survey by the Air Force Materiel Command endorse the ability of the proposed new tunnels to provide value added to the development of future military aircraft (Leaf, 1994).

RECAP OF THE FINDINGS AND RECOMMENDATIONS OF THE NATIONAL AERONAUTICAL TEST FACILITIES STUDY

The decision to build high Reynolds number subsonic and transonic tunnels must balance the need for more-capable facilities with specific performance parameters, the costs of building and operating new facilities, and the economic benefits that are likely to result. Based on the analyses conducted by the NFS; other factors discussed in this report; and the benefits that the United States could derive from the tunnels in terms of balance of trade, employment, and economic activity, the ASEB recommends proceeding with the design and development of new subsonic and transonic facilities while more fully exploring the items recommended herein for further study. Furthermore, the ASEB has determined that the key thrusts of the NFS are justified. These key points are as follows:

- Significant aerodynamic performance improvements are achievable, and the nation that excels in the development of these improvements has the opportunity to lead in the global market for commercial and military aircraft.
- New high Reynolds number ground test facilities are needed for development testing in both the low speed and transonic regimes to assure the competitiveness of future commercial and military aircraft produced in the United States.
- Along with the procurement of new facilities, selected upgrades to existing

facilities are also essential to adequately support future research and development programs.

- The United States should acquire premier development wind tunnels rather than rely on continued use of European facilities.
- Additional action is necessary to adequately address future requirements for supersonic, hypersonic, and aeropropulsion test facilities.

The ASEB urges taking the additional actions noted below. These actions go beyond the recommendations contained in the NFS report.

- The Wind Tunnel Program Office should conduct trade studies to evaluate design options associated with the proposed new low speed and transonic wind tunnels (see Recommendation 2-1).[26] In addition, the Wind Tunnel Program Office should ensure that the new transonic and low speed facilities will be able to adequately support development of supersonic aircraft such as high speed civil transports by investigating flight characteristics during takeoff, acceleration, transonic flight over land, and landing.
- NASA and the Department of Defense should continue support for facility research in the subsonic and transonic regimes.
- NASA and the Department of Defense should expand coordinated efforts that involve aerodynamic test facilities, computational methods, and flight test capabilities.
- NASA and the Department of Defense should develop a continuing mechanism for long-term planning of aeronautical test and evaluation facilities.

A complete listing of the findings and recommendations of the National Aeronautical Test Facilities Study appears below.

U.S. Response to Changing Facility Requirements

Finding 1-1: The history of aviation offers several lessons learned that are relevant to the current debate on aeronautical ground test facilities.

- The future of rapidly evolving disciplines and the types of facilities they will require are often uncertain.
- Advanced aeronautical ground test facilities go hand-in-hand with leadership in aeronautical design and production.
- Historical precedent exists for special appropriations that provide full government funding of major aeronautical ground test facilities needed by industry to conduct development testing of military and commercial products.

Recommendation 1-1: *Planning for a new generation of premier aeronautical ground test facilities should consider how the lessons learned from similar past efforts apply to the current situation.*

Subsonic and Transonic Facilities

Finding 2-1. With regard to low speed and transonic facilities, the findings of the Aeronautics and Space Engineering Board are as follows:

a. Significant aerodynamic performance improvements are achievable, and the nation that excels in the development of these improvements has the opportunity to lead in the global market for commercial and military aircraft.
b. New high-Reynolds-number ground test facilities are needed for development testing in both the low speed and transonic regimes to assure the competitiveness of future commercial and military aircraft produced in the United States. These facilities will also contribute to the development testing of supersonic aircraft, such as high speed civil transports, by characterizing flight characteristics during

[26] NASA has established a Wind Tunnel Program Office at Lewis Research Center. This office, which reports to the NASA Administrator, is now working with industry to develop an acquisition strategy for building two new low speed and transonic wind tunnels, as recommended by the National Facilities Study.

takeoff, acceleration, transonic flight over land, and landing.

c. Facility configuration trade-off studies conducted by the NFS on Reynolds number, productivity, and life cycle cost appear to be sound. Additional configuration studies are needed for both the subsonic and transonic tunnels. Each assessment should take into account the differences in tunnel and model parameters between subsonic and transonic wind tunnel testing. These additional assessments should cover the following topics:

(1) using a single tunnel to test both the low speed and transonic speed regimes;
(2) making incremental changes to tunnel operating pressures (e.g., from 5 to 5.5 atmospheres) to allow reduction of facility size and cost without sacrificing Reynolds number capability;
(3) including within the baseline design the ability to provide future growth in Reynolds number capability through use of higher operating pressures (up to 8 atmospheres), reduced temperatures (down to about −20°F), and/or a heavy test gas (such as SF_6); and
(4) improving the robustness of the tunnel designs by designing facility components with margin for growth in pressure and operating power to improve component reliability, increase facility lifetime, and facilitate future upgrades.

d. Completion of planned upgrades to existing facilities is an essential complement to the acquisition of new facilities.

e. Facility research on high pressure wind tunnels and other wind tunnel concepts should continue. These efforts should include research related to high pressure wind tunnel models.

f. Scaling methods are essential to current design processes. Even with new facilities, scaling of ground test results will still be necessary to accommodate full-scale simulation of very large or innovative aircraft designs that may be developed in the future. Coordinated efforts to develop improved scaling methods that use wind tunnel testing, computational methods, and flight tests should be expanded.

g. New facilities offer potential benefits to the U.S. economy and the global environment that are large compared with the investments required.

Recommendation 2-1. *The ASEB recommends the following:*

a. NASA's Wind Tunnel Program Office should proceed with the design and development of new subsonic and transonic facilities while conducting the four design trade studies noted in Finding 2-1c during the design phase of the wind tunnel program. It should also ensure that the detailed designs of the proposed new wind tunnels will adequately support requirements related to factors such as noise, turbulence, simulation of jet-engine flows, low speed testing of supersonic aircraft, and testing of military aircraft and systems.

b. NASA should complete planned upgrades to existing facilities as soon as possible.

c. NASA and the Department of Defense should continue facility research on high pressure wind tunnels and other concepts.

d. NASA and the Department of Defense should expand efforts to develop advanced scaling methods that involve wind tunnel testing, computational methods, and flight tests.

Supersonic Facilities

Finding 3-1: U.S. supersonic wind tunnels adequately satisfy most current and potential test requirements. Shortfalls exist in productivity, reliability, maintainability, and laminar flow test capabilities.

Recommendation 3-1: *The Aeronautics and Space Engineering Board recommends upgrading the 16S facility at Arnold Engineering Development Center to include continued improvements in the 16S/16T motor drive and compressor systems. Research to define test requirements and develop practical facility concepts for supersonic laminar flow technology should be continued.*

Propulsion Facilities

Finding 4-1: Current propulsion facilities in the United States are world class and adequate to meet current and near-term test requirements.

Recommendation 4-1: *Communication between the government agencies that operate national aeropropulsion facilities and industry should be continued to assure propulsion facility readiness relative to future requirements. In particular, the ASEB concurs that the study proposed by the NFS should be conducted.*

Hypersonic Facilities

Finding 5-1: The National Facilities Study report is consistent with prior studies of hypersonic test capabilities.

Recommendation 5-1: *To address the hypersonic ground test deficiencies identified in previous studies, the ASEB endorses the objectives of the two-phase program recommended in the National Facilities Study report.*

Additional Considerations and Future Directions

PRICING POLICY & FACILITY USAGE

Finding 6-1: Pricing policy can have a significant impact on user fees. The size of user fees, in turn, is likely to influence user demand, which is an important factor in planning the construction of new facilities.

Recommendation 6-1: *The government should make pricing policy an integral part of the decision-making process that it uses for major new ground test facilities. The government should carefully consider any subsequent changes in pricing policy to ensure that they do not compromise the economic viability of its facilities.*

FACILITY MANAGEMENT

Finding 6-2: Management structure, including agency sponsorship, can materially impact the ability of large acquisition programs to meet their cost and schedule goals. Management structures that feature oversight or sponsorship by multiple agencies or organizations tend to increase schedule and cost risk, especially for expensive, long-term programs.

Recommendation 6-2: *The government should select a facility management structure that minimizes cost, schedule, and programmatic risk.*

ACQUISITION STRATEGY

Finding 6-3: Construction of new facilities using an acquisition process unimpaired by the full weight of federal acquisition regulations would reduce cost and schedule requirements.

Recommendation 6-3: *The proposed low speed and transonic wind tunnels should be acquired using the most efficient combination of federal and commercial acquisition practices.*

SITE SELECTION

Finding 6-4: For facilities such as the proposed low speed and transonic wind tunnels, which will require large technical staffs and huge amounts of energy, selection of a less-than-optimum site has the potential to degrade the efficiency and increase the cost of facility construction and operation, particularly if power availability restricts wind tunnel operating hours.

Recommendation 6-4: *If a decision is made to build the proposed tunnels, the site selection process should proceed in a timely fashion. In order to optimize the cost-effectiveness of the proposed new wind tunnels, the process should focus on objective criteria—such as those contained in Volume II-A of the NFS final report—that are directly related to the mission of the proposed facilities.*

OVERALL PRIORITIES

Recommendation 6-5: *The ASEB recommends acquisition of new transonic and subsonic wind tunnels as the number one priority in the area of development wind tunnels. If both facilities are not acquired in parallel, then the transonic facility should lead the subsonic facility. Research related to subsonic, transonic, supersonic, and hypersonic facilities should be prioritized and executed as coordinated efforts that involve other related research programs conducted by*

NASA and the Department of Defense. A study of future propulsion facility requirements should be pursued independently of these other activities.

SCOPE OF CURRENT STUDIES

Finding 6-6: The National Facilities Study and this National Research Council study have not analyzed requirements for many types of important aeronautical test facilities, such as vertical flow spin tunnels, rotorcraft whirl towers, computational facilities, and flight test facilities.

Recommendation 6-6: *The results of the National Facilities Study and this National Research Council study should not be used to assert that types of facilities that were outside the scope of their deliberations are unimportant to the future of the U.S. aeronautics industry, even though such facilities are not discussed in the resulting reports. The work of the NFS Task Group on Aeronautical R&D Facilities should be augmented to develop a comprehensive view of future requirements for aeronautical ground test facilities. Furthermore, any effort to develop new wind tunnels should be structured to take maximum advantage of the synergy that exists between ongoing advances in the technologies associated with ground, flight, and computational facilities.*

INTEGRATED TEST AND EVALUATION METHODOLOGIES

Finding 6-7: Judicious use of more-effective test and evaluation methodologies can maximize the impact of new and upgraded facilities on the competitiveness of the aeronautics industry.

Recommendation 6-7: *Facility development efforts should ensure that new and improved physical assets are designed to accommodate foreseeable advances in test methodologies and other disciplines that will affect facility effectiveness. This will require coordinating advances in ground test capabilities with planned improvements in computational and flight test capabilities.*

NON-TECHNICAL AERONAUTICAL FACILITY ISSUES

Finding 6-8: The service life of major new facilities could easily extend to the middle of the next century. Furthermore, the need for long-range planning of facility needs is a recurrent theme in past studies of aeronautical ground test facilities. Assigning the responsibility to study future requirements and conduct long-range planning to a permanently established body would provide greater continuity than the current process of relying on intermittent, ad hoc committees. Delegating this responsibility to an existing body would achieve the desired goal without adding to the number of government advisory panels.

Recommendation 6-8: *Long-range planning of future requirements for national aeronautical ground test facilities should be carried out on a continuing basis by a permanently established body such as an interagency advisory group or standing committee. The designated body should work with relevant government agencies and industrial groups to resolve policy and procedural issues that diminish the effectiveness of current and future facilities.*

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APPENDIX A: National Facilities Study Terms of Reference

I. BACKGROUND

The United States is increasingly challenged by advances in technologies that will affect its global competitiveness in virtually all economic sectors. Preeminent among these are advances in aerospace technology. These advances are paced by modern highly productive research, development and operational facilities. Recognizing this situation, on November 13, 1992, the NASA Administrator initiated the development of a comprehensive and integrated long-term plan for future aerospace facilities. This integrated plan would be accomplished in partnership with other Government agencies, industry, and academia to ensure that the facilities are world-class and to avoid duplication of effort. He contacted top officials in the Departments of Defense, Energy, Transportation, Commerce, and the National Science Foundation inviting them to participate in the development of the plan and the appropriate working groups. The Administrator proposed an Oversight Group chaired by John R. Dailey, NASA Associate Deputy Administrator, with representation from DoD, DOT, DOE, DOC and the NSF. Each of the agencies responded with nominations of individuals to serve on the Oversight Group and provide support on Task Groups to establish detailed plans. This Terms of Reference document provides the coordinated charter for development of the Aerospace Facilities Plan.

II. PURPOSE

To formulate a coordinated National Plan for world-class aeronautical and space facilities that meets the current and projected needs for commercial and Government research and development, and for Government and commercial space operations.

III. SCOPE

The plan will include a catalogue of existing Government and industry facilities that support aeronautics and astronautics research, development, testing, and operations. International facilities will also be catalogued to determine capability relative to U.S. facilities and applicability to address U.S. facility shortfalls.

The plan will include a requirements analysis which will consider current and future Government and commercial industry needs as well as DoD and NASA mission requirements, through the year 2023, and specifically will address shortfalls in existing capabilities, new facility requirements, upgrades, consolidation, and phase out of existing facilities. All new facility requirements and upgrades will be prioritized and detailed schedules and total funding will be specified. Joint management schemes, life cycle costs, and siting requirements will be fully evaluated.

Joint funding between agencies and Government/industry will be considered. Shared usage policies will be developed where nonexistent.

Costing, definitions, evaluation methodology and dollar threshold for facility inclusion in review will be approved by the Oversight Group.

IV. ORGANIZATION

An Oversight Group, chaired by NASA with a DoD Vice-Chairman and including membership from DOE, DOT, DOC and the National Science Foundation, will have responsibility for implementing this TOR and plan development. The secretary will be nominated by NASA.

The chairman will appoint a study director for executing this TOR. This person will be responsible for conducting the study and its schedule, coordinating participation, integrating all inputs, preparing the final products, and providing those products to the Oversight Group.

To assist the study director, four task groups will be established. These are the Aeronautics R&D Task Group, the Space R&D Task Group, the Space Operations Task Group and the Facilities Costing and Engineering Group. The task groups will be co-chaired by NASA and DoD. All participating agencies will provide representatives to each task group. The task groups will have the authority to establish working groups to assist them in their tasks. Membership on the task and working groups will be limited to Government employees and participation is optional, except for NASA and DoD. The Aeronautics Task Group is an exception because of the special need to address commercial transport aircraft. For this reason experts from private industry participate as Special Government Employees, and the task group will function in accordance with the Federal Advisory Committee Act. Throughout the study, however, industry and academic inputs and advice should be actively solicited.

The Oversight Group will provide guidance to the task groups, serve as the coordination mechanism, perform periodic progress reviews, resolve disputes or misunderstandings that may arise between the agencies under the memorandum, and recommend an integrated plan for agency approval. The task groups will have responsibility for planning, directing, and providing recommendations in their particular discipline area.

Each agency will utilize its own reporting and tasking authority and will bear its and its employees' own costs for participation. Activities shall be subject to the availability of funds and personnel of each party.

V. PRODUCT

The study director will provide a summary report to the Oversight Group incorporating input from each of the task groups that includes a compendium of current facilities and capabilities; identification of shortfalls as a function of current and projected needs; and recommendations and rationale for new facilities, upgrades, consolidation, or closure of existing facilities. Recommendations will include cost impacts, either as investment costs or savings, and any other considerations that would bear on the decision (i.e., national security concerns, technology transfer, proprietary data rights, commercial competitiveness, etc.). The summary report will also include any recommendations relative to a policy nature, such as shared usage, common costing, and management and operation.

Upon approval by the Oversight Group, each report will be forwarded for agency approval. Final reports will be approved at the Deputy Administrator/Under Secretary level or equivalent. For the DoD, the responsible authority is the Under Secretary of Defense for Acquisition. Final reports should reflect a national viewpoint endorsed by NASA, DoD, DOC, DOT, DOE, and NSF.

VI. SCHEDULE

Interim Task Group Reports (to support FY '95 budget decisions)	July 1993
Final Task Group Reports	January 1994
Oversight Approval - Task Group Reports	February 1994
Coordination of Individual Reports	March 1994
Approval of Individual Reports	March 1994

VII. APPROVAL, AMENDMENT, AND TERMINATION

This Terms of Reference shall enter into force upon the signature of all Parties and shall remain in force through July 1994. It may be modified, extended, or terminated by mutual consent of all parties.

Original Approved by:

Department of Commerce, David Barram, Deputy Secretary
Department of Defense, William J. Perry, Deputy Secretary
Department of Energy, Bill White, Deputy Secretary
Department of Transportation, Mortimer L. Downey, Deputy Secretary
National Aeronautics and Space Administration, Daniel S. Goldin, Administrator

APPENDIX B: National Aeronautical Test Facilities Workshop Participants

The following individuals participated in the National Aeronautical Test Facilities Workshop, held May 16–18, 1994 at the National Research Council. This workshop allowed members of the Aeronautics and Space Engineering Board to discuss future needs for aeronautical ground test facilities with key members of the National Facilities Study Task Group on Aeronautical R&D Facilities and other members of the aeronautics community. The objective of the workshop was to examine the status of, and future requirements for, aeronautical ground test facilities in the context of the work of the Task Group on Aeronautical R&D Facilities. Discussions focused on specific issues raised by members of the Aeronautics and Space Engineering Board and other workshop participants.

Dr. Joseph P. Allen, Member, Aeronautics and Space Engineering Board
Mr. Alan Angleman, Staff, Aeronautics and Space Engineering Board
Dr. Richard W. Barnwell, NASA Langley Research Center
Dr. Judson R. Baron, Massachusetts Institute of Technology
Dr. H. Lee Beach Jr., NASA Langley Research Center
Mr. James M. Beggs, Member, Aeronautics and Space Engineering Board
Dr. Frederick S. Billig, Johns Hopkins University Applied Physics Laboratory
Dr. Guion S. Bluford, Jr., Member, Aeronautics and Space Engineering Board
Mr. Seymour M. Bogdonoff, Princeton University
Mr. John V. Bolino, Office of the Under Secretary of Defense (Acquisition)
Mr. John K. Buckner, Member, Aeronautics and Space Engineering Board
Mr. Dennis M. Bushnell, NASA Langley Research Center
Mr. Armand J. Chaput, Lockheed-Fort Worth Company
Mr. Richard Circle, Lockheed
Ms. JoAnn Clayton, Director, Aeronautics and Space Engineering Board
Dr. Eugene Covert, Massachusetts Institute of Technology
Dr. Bill Davis, Calspan Corporation
Mr. Richard A. Day, Boeing Commercial Airplane Group
Dr. Alexander Flax, National Academy of Engineering
Col Larry Gravis, Arnold Engineering Development Center
Mr. Ronald Hendrickson, Grumman Aerospace & Electronics
Mr. Gregory Henry, Office of Management and Budget
Mr. Ken Hoefs, Boeing Commercial Airplane Group
Mr. Curtis Kessler, Wright Laboratory
Mr. Richard L. Kline, NASA Headquarters
Mr. Bernard L. Koff, Study Chairman and Member, Aeronautics and Space Engineering Board
Gen Donald J. Kutyna, Member, Aeronautics and Space Engineering Board
Dr. Marion L. Laster, Arnold Engineering Development Center
Mr. Glen Lazalier, Arnold Engineering Development Center/Sverdrup
Lt Gen Howard Leaf, Air Force Test and Evaluation
Mr. Frank T. Lynch, McDonnell Douglas Aerospace
Mr. Robert R. Lynn, Member, Aeronautics and Space Engineering Board
Dr. Artur Mager, Consultant
Mr. C. Julian May, Member, Aeronautics and Space Engineering Board
Mr. L. Wayne McKinney, NASA Headquarters
Mr. Duane T. McRuer, Chairman, Aeronautics and Space Engineering Board

Mr. Ted Morrison, Staff, Aeronautics and Space Engineering Board
Mr. Victor L. Peterson, NASA Ames Research Center (retired)
Mr. John Rampy, Arnold Engineering Development Center
Dr. Robert Rosen, NASA Ames Research Center
Mr. Lawrence J. Ross, NASA Lewis Research Center
Dr. Paul E. Rubbert, Boeing Commercial Airplane Group
Mr. Norman Scaggs, Wright Laboratory
Mr. Charles Schilling, NASA Headquarters
Mr. Robert E. Smith, Jr., Consultant
Dr. Alexander Smits, Princeton University
Mr. Elton Thompson, Consultant, Micro Craft, Inc.
Mr. Robert H. Widmer, General Dynamics (retired)
Mr. Louis J. Williams, NASA Headquarters
Mr. Peter Wooler, Northrop Corporation
Mr. Mark V. Zagarola, Princeton University

APPENDIX C

National Facilities Study Participants

OVERSIGHT GROUP

John R. Dailey, Chairman, NASA/HQ
Charles E. Adolph, Vice Chairman, DoD/OSD
Sally H. Bath, DOC
E. Fenton Carey, DOE
Wesley L. Harris, NASA/HQ
Jimmie D. Hill, DoD/USAF
James J. Mattice, DoD/USAF
Richard McCormick, DoD/USAF
Donald R. Trilling, DOT

TASK TEAM

Richard L. Kline, Director, NASA/HQ
Charles R. Schilling, Assistant, NASA/HQ

AERONAUTICAL R&D FACILITIES TASK GROUP

H. Lee Beach, Co-Chair, NASA/LaRC
John V. Bolino, Co-Chair, DoD/OSD
L. Wayne McKinney, Exec. Sec., NASA/HQ
William S. Clapper, G.E. Aircraft Engines
Richard A. Day, Boeing Commercial Airplane Co.
John E. King, McDonnell Douglas Aerospace
David Poferl, NASA/LeRC
John Rampy, DoD/AEDC
Robert Rosen, NASA/ARC
William L. Webb, UT/Pratt & Whitney
Louis J. Williams, NASA/HQ

Aerodynamics/Aeroacoustics Working Group

Louis Williams, Chairman, NASA/HQ
Lynn Laster, Dept. Chair, AEDC
William Eckert, Exec. Sec., NASA/HQ
Suey Yee, Exec. Sec., NASA/HQ
Zac Applin, NASA/LaRC
Nancy Bingham, NASA/ARC
Joe Chlebanowski, Naval Surface Warfare Center
William Davis, CALSPAN Corp., AEDC
Richard A. Day, Boeing Commercial Airplane Co.
Bobby Delaney, GE Aircraft Engines
Donald Dusa, GE Aircraft Engines
Arthur Fanning, Boeing Commercial Airplane Co.
Heinz Gerhardt, Northrop
Edward Glasgow, Lockheed
Blair Gloss, NASA/LaRC
Dabney Howe, Northrop
Frank Lynch, McDonnell Douglas Aerospace -Transport Unit
Luis Miranda, Lockheed
Leroy Presley, NASA/ARC
William Stamper, NASA/HQ
Lewis Surber, Wright Laboratory
Jim Yu, NASA/LaRC

Hypersonic Working Group

Keith Richey, Chairman, Wright Laboratory
Carlos Tirres, Exec. Sec., AEDC
Jim Arnold, NASA/ARC
Dennis Bushnell, NASA/LaRC
Michael DeAngelis, NASA/DFRC
Jerry Roffe, General Applied Science Laboratory
Lynn Laster, AEDC

Bob Voisinet, Naval Surface Warfare Center
Paul Waltrup, Johns Hopkins University
James Mark, McDonnell Douglas Aerospace

Propulsion Working Group

David Poferl, Chairman, NASA/LeRC
David Duesterhaus, Co-Chair, DoD/AEDC/ DOPT
John Bennett, General Electric
Bruce Block, NASA/LeRC
Stan Blyskal, Navy Air Warfare Center
Lee Coons, UT/Pratt & Whitney
Robert Delaney, General Electric
John Facey, NASA/HQ
Richard Hill, Wright Laboratories
Glen Lazalier, Sverdrup Technologies/AEDC

Strategy Working Group

Robert Rosen, Chairman, NASA/ARC
Sally Bath, DOC
John Bolino, DoD/ACQ
Tom Edwards, NASA/LeRC
Parker Horner, USAF
Doug Nation, DoD
Mark Brenner, DOC
Lynn Laster, AEDC
Arv Larson, Walcoff and Associates

SPACE R&D FACILITY TASK GROUP

Dennis Granato, Co-Chair, DoD/OSD
Peter Lyman, Co-Chair, NASA/HQ
John C. Mankins, Exec. Sec., NASA/HQ
Frederick E. Betz, DoD/USN
Dale Bradley, DoD/BMDO
J. Stuart Fordyce, NASA/LeRC
W.H. Lewis, NASA/HQ
Gordon R. Middleton, DoD/USAF
H. V. McConnaughey, NASA/MSFC
E. Clayton Mowry, DOC
C.S. Rappaport, DOT
Michael Toole, DoD/USAF
Robert Waldron, DOE

SPACE OPERATIONS FACILITY TASK GROUP

Richard McCormick, Co-Chair, DoD/USAF
Gerald W. Smith, Co-Chair, NASA/SSC
Nancy Bray, Exec. Asst., NASA/KSC
Laura Kennedy, Exec. Asst., DoD/USAF
Stanley Mushaw, Exec. Asst., DoD/USAF
David W. Harris, NASA/HQ
Larry Heacock, NOAA
Samuel D. Malone, NASA/HQ
Richard W. Scott, Jr., DOT
Ralph Spillinger, NASA/HQ

FACILITIES COSTING & ENGINEERING TASK GROUP

Connie Brown, Co-Chair, DoD/USAF
Billie J. McGarvey, Co-Chair, NASA/HQ
William W. Brubaker, NASA/HQ
Francis X. Durso, NASA/HQ
James Vitagliano, NASA/HQ

APPENDIX D: AERONAUTICAL SPEED REGIMES AND TEST PARAMETERS

The purpose of this appendix is to provide a rudimentary explanation of aeronautical speed regimes and some of the key parameters used to define aerodynamic wind tunnels.

Many important parameters apply to the design and operation of wind tunnels. Among these are Mach number, Reynolds number, flow quality, wall temperature ratio, productivity, noise levels, and spectral signatures. Mach number and Reynolds number are especially important to the accuracy of test data, but it is very expensive to build facilities that accurately simulate these parameters for large, high-speed aircraft.

MACH NUMBER

Mach number is defined as a ratio of vehicle speed to the speed of sound. It is a function of gas temperature and specific heat ratio (Equation 1). For ground tests, wind tunnel free stream velocity is used to approximate vehicle speed.

$$M = \frac{V}{a} = \frac{V}{\sqrt{\gamma g_c R T}}$$

(1) Mach Number
M = Mach number
V = Vehicle speed
a = Speed of sound (nominally 750 mph at standard temperature and pressure)
γ = Specific heat ratio (of the atmosphere or test gas)
gc = Acceleration of gravity
R = Gas constant (of the atmosphere or test gas)
T = Absolute temperature (of the atmosphere or test gas)

Extremely low temperatures can produce high Mach numbers at low free stream velocities. However, wind tunnel simulation of Reynolds numbers is not achieved by raising Mach number alone (see “Reynolds Number” below).

SPEED REGIMES

There are four speed regimes related to aerodynamic testing. The boundaries between the speed regimes are rather vague, though each speed regime does have its own qualities that sets it apart from the others. The speed regimes are summarized as follows:

- *Subsonic flight: $0 < M < 0.8$*

At less than about Mach 0.8, air can usually be treated as an ideal, incompressible gas for slender aircraft configurations. There are usually no shock waves to complicate design and analysis, although they can appear at velocities as low as Mach 0.3 for surfaces with high lift coefficients or in aircraft configurations that are thick or blunt or that otherwise produce a large change in pressure or velocity of the flow.

- *Transonic flight: $0.8 < M < 1.0$–1.2*

Above roughly Mach 0.8, the aircraft or model begins to compress the air enough to generate shock waves on portions of the wing and fuselage. Some regions may have supersonic flows, while in other areas the flow may still be sonic or even subsonic. These shock waves usually begin on either the nose or the location of the peak negative pressure on the wing. However, elsewhere along the body of the aircraft or along the wing itself, areas may exist where the air is still below the speed of sound. As the aircraft velocity increases above Mach 1.0, these shock waves tend to slope toward the wing and body surfaces.

- *Supersonic flight: 1.0–1.2 < M < 5*

Depending on the thickness and sweep of the wang and the slenderness of the configuration, at a speed somewhat above Mach 1.0 (typically 1.2–1.5), the general flow field becomes essentially supersonic.

- *Hypersonic flight: M > 5*

As velocities increase past Mach 5, test conditions for complete simulation must match additional fluid properties such as the specific heat ratio, the gas temperature, and the ratio of body-wall temperature to fluid total temperature. At hypervelocities (above about Mach 13) radiation heating and thermodynamic nonequilibrium effects become significant, and the air will start to ionize and dissociate. Interactions within the airstream and between the airstream and vehicle become much more complicated.

REYNOLDS NUMBER

Reynolds number is the ratio of the inertia forces to the viscous forces that a fluid exerts on a surface as it flows past. Reynolds number is directly related to Mach number (Equation 2).

$$\mathrm{Re} = \frac{VL\rho}{\mu} \approx \frac{MLP\sqrt{\gamma}}{TC\sqrt{g_c R}}$$

(2) Reynolds Number
Re = Reynolds number
L = Characteristic length (of the aircraft or model in the direction of flow)
ρ = Gas density
μ = Dynamic viscosity coefficient (of the test gas)
P = Gas pressure
C ≈ The ratio between μ and $T^{1/2}$ (C is itself a weak function of temperature)
See Equation (1) for definition of other variables.

During wind tunnel tests, Reynolds number should be consistent with full-scale flight conditions. Otherwise, test flows may behave differently than under actual flight conditions.

Wind tunnel models must be small enough to avoid creating flow blockages and associated wall effects. As model scale is reduced, the characteristic length of the model is also reduced, and test conditions must be altered to restore flight Reyno number. For example, in order to test a quarter-scale model at flight Mach and Reynolds numbers, wind tunnel pressure must be increased and temperature must be decreased by a combined factor of four.

For practical reasons, few wind tunnels are designed for pressures higher than 3 to 5 atmospheres. Beyond this, atmospheric thermal effects arise, requiring large amounts of cooling in order to keep the simulation within testing parameters. The structural strength of the wind tunnel pressure vessel, the model, and the model support structure must also be increased to withstand the static and dynamic loads that high pressures generate. Thus, the construction and operational costs associated with large high-pressure facilities can be substantial.

cool

Nonetheless, some research facilities use extremely high pressures (up to hundreds of atmospheres) or cryogenic temperatures to conduct testing at extremely high Reynolds numbers with small or moderately-sized models. Practical limitations, however, make these facilities unsuitable as development facilities. Development testing requires easy access to wind tunnel test sections to make model adjustments between test runs. High pressure facilities require long periods of time to depressurize and repressurize the test section before and after model adjustments. Cryogenic facilities require time to and thermally stabilize test conditions after opening the test section for human access. Furthermore, both types of facilities require specially designed models to withstand the extreme test conditions.

Some wind tunnels use nitrogen, helium, freon, or sulfur-hexafluoride (SF_6) as test gases. The higher molecular weight of gases heavier than air increases the Reynolds number capability. In some cases, using gases other than air also makes it easier to cool the flow stream, which contributes to higher Mach and Reynolds number capability. However, use of alternative test gases complicates the interpretation of data to predict vehicle performance in air, and this process introduces uncertainty in the final results. Alternative gases may also raise safety, cost, and environmental concerns. Freon, for example, is no longer a viable option because of environmental considerations. The safety precautions needed with test gases that are corrosive or otherwise dangerous also reduce productivity. Because of these factors, gases other than air are not currently a practical alternative for large-scale development wind tunnels.

Adjusting flow velocity is sometimes used to adjust Reynolds number, but this means the data is no longer representative of actual flight speed. As free stream velocity approaches the speed of sound in the wind tunnel, compressibility effects can affect model aerodynamics in ways that will not appear on a full-scale vehicle. Experience has shown that combining data from different tests (one at flight Reynolds number, the other at flight Mach number) is not nearly as effective as conducting a single test that matches both parameters.

FLOW QUALITY

Wind tunnel flow quality also directly impacts the validity of test data. Highly turbulent flows will provide significantly different results than tests using low turbulence flows or smooth (or “laminar”) flows. Laminar flows are most representative of ambient conditions in the atmosphere, but laminar flow facilities are difficult and expensive to build.

PRODUCTIVITY

Wind tunnel productivity is usually quoted in terms of polars per occupancy hour. A polar is generally defined as a set of 25 data points, where each data point is obtained at a different value of a single independent variable. Occupancy hours include all of the time that a wind tunnel test section is dedicated to a particular test. This includes model set-up, testing, and tear-down.

Most of the time occupied in a typical wind tunnel experiment involves setting up the model in the tunnel. In most facilities, the tunnel is unable to conduct any testing while test set up, calibration, etc., is taking place. In other words, an extremely large and expensive facility may sit idle for days while a few technicians and engineers tinker with a test model. This situation contributes to the low productivity of many large wind tunnels in the United States.

The use of removable, interchangeable test carts can dramatically increase productivity. Carefully designed and engineered test carts allow experimental set up to begin in an adjacent facility while wind tunnel testing on other models can proceed without impediment. As soon as one test program is finished, the test carts can be exchanged, and testing can quickly resume on the next model. Such facilities cost more to build, but overall cost per polar is reduced if demand is high enough to take advantage of the higher productivity.