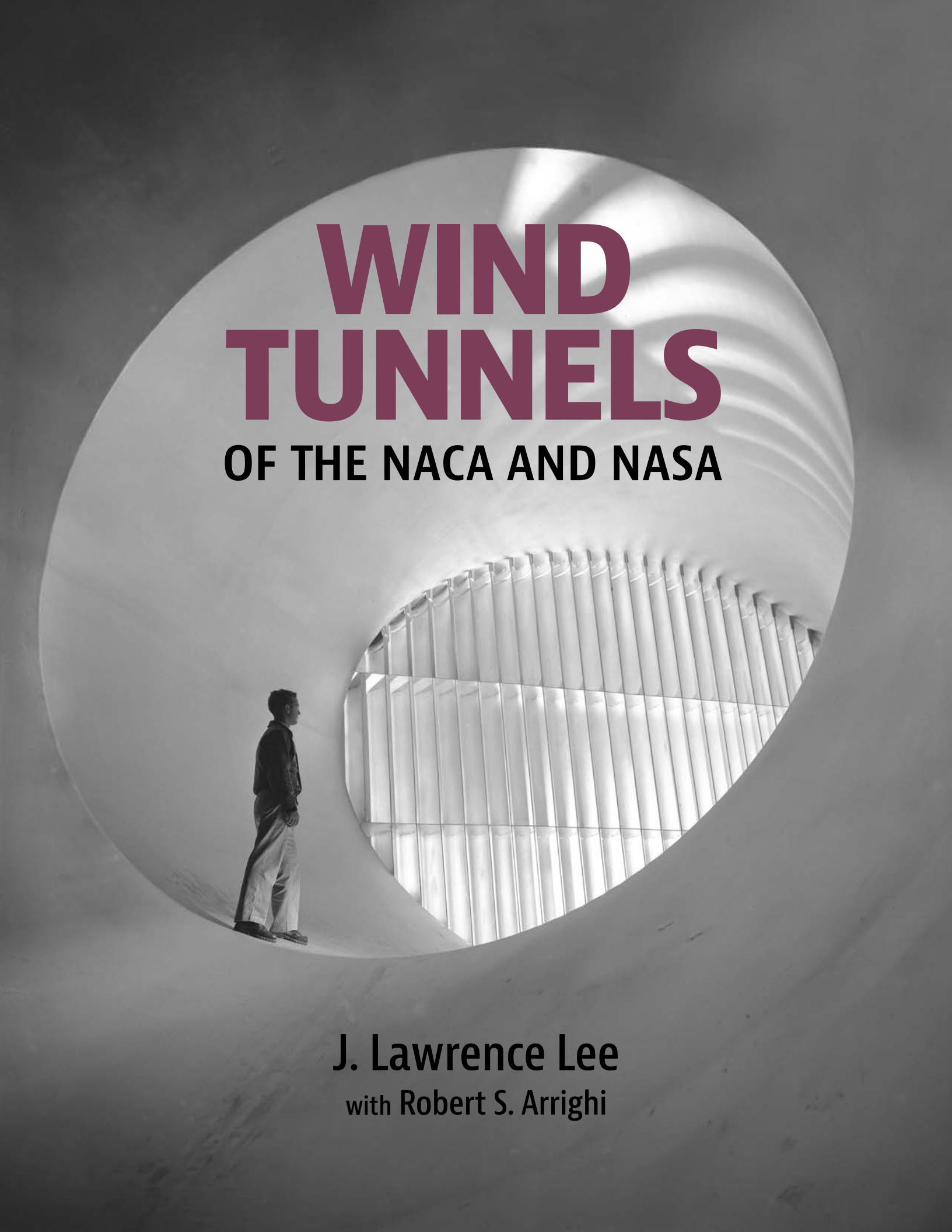
WIND TUNNELS

OF THE NACA AND NASA



J. Lawrence Lee

with Robert S. Arrighi

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J. Lawrence Lee

So many authors have said that their books were not the product of one person that it might be taken as a cliché, but in truth, it is an understatement of grand proportion, and it is certainly true for this book. From a discussion with my major professor about wind tunnels as a dissertation topic in graduate school to the interviews, guidance, documents, and reviews of this manuscript by so many current and former NASA employees, I find myself indebted to dozens of fine people who have aided and supported me during a long journey. I want to thank every one of you. My fear is that I will inadvertently omit someone, but I will have to trust that any such individual will know that my error was unintentional and forgive me.

During my years as a practicing mechanical engineer, I had a few occasions to visit wind tunnels, and I had assisted a friend with a wind tunnel test project as an undergraduate engineering student. But my engineering career led me in other directions, and I did not think much about wind tunnels until graduate school more than two decades later. I was fortunate enough to have renowned aerospace historian James R. Hansen as my major professor, and he suggested that I take a look at wind tunnels as a dissertation topic. It proved to be an excellent suggestion, so I must thank Jim for that inspiration, as well as for his guidance and encouragement throughout the process, not to mention the opportunity to work with him on a very complementary project for NASA that greatly aided my research efforts. The other members of my committee, William Trimble and Stephen McFarland, were likewise unfailing in

their support and knowledgeable assistance. I am very fortunate to know all three as friends and colleagues.

The list of those associated with NASA who willingly offered their knowledge and assistance is a long one. It must start with former Federal Preservation Officer Tina Norwood and Stephen Garber, former Historian at NASA Headquarters in Washington. Tina, who transferred to another position with NASA shortly before the manuscript was completed, is responsible for initiating the project, and Steve somehow managed to keep me headed "into the wind." Both exhibited an amazing amount of patience and enthusiasm for the project! Tina's successors, Kathy Callister and Rebecca Klein, also displayed great enthusiasm for this book. In the Aeronautics Research Mission Directorate at Headquarters, Tony Springer and Michael Mastaler spent hours reviewing my drafts, and their amazing attention to detail saved me from many errors. Additional reviews by many people at the various centers also kept my mistakes from finding their way into print. I thank you all. Though I hope they are few, any errors that remain are, of course, solely my responsibility.

Numerous people at the various NASA research centers did more than I could have hoped for to further my research endeavors. The wealth of time, energy, and knowledge shared with me by so many can never be fully repaid, and I hope that I have been able to absorb and comprehend at least most of what was so freely given and that their wisdom informs and flavors this entire book. Their intimate involvement with these tunnels and their colleagues is what brings these machines to life. This book would hardly have been worth printing without their insights, contributions, corrections, and guidance. At the Langley, Ames, Glenn, and Marshall Centers, as well as the Jet Propulsion Laboratory, current and retired engineers, technicians, historians, and archivists freely shared their experiences, knowledge, and documents that would otherwise have been difficult, if not impossible, to find and fully comprehend. Each one exhibited a dedication to NASA's mission and a passion for its history at every opportunity. In these bright, affable people, this nation has a treasure beyond what it knows.

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I must also thank my employer, the National Park Service's Historic American Engineering Record, particularly Heritage Documentation Program Chief Richard O'Connor, for supporting this project and generously granting the time and resources needed to pursue it for a longer period than any of us anticipated. No one could have wished for more support.

Without a doubt, the one person who offered the greatest reservoir of encouragement and long-suffering through the seemingly endless process of researching and writing this book is my wife, Judy. I simply could not have stayed the course without her unfailing support and ability to keep at least part of me connected to my world and my faith, and I dedicate this book to her. Thanks, my love!

Robert Arrighi

I first met Larry Lee in February 2007 when he visited Glenn Research Center to inspect the wind tunnels, meet facility managers, and obtain research materials for this project. Larry's genteel nature and enthusiasm for wind tunnels made the visit memorable for many of us. I was working on a history of the Altitude Wind Tunnel at the time, however, and the *Wind Tunnels of the NACA and NASA* project soon dropped off my radar. I was pleasantly surprised in the summer of 2022 when NASA's Chief Historian, Brian Odom, asked me to see this long-overdue project to its completion. So, first and foremost, I would like to thank Larry Lee for the exhaustive research and dedication that produced this exceptional book.

I would like to thank Tina Norwood, Stephen Garber, James Anderson, and Brian Odom at NASA Headquarters for deciding to resurrect this long-dormant project and asking me to carry it through to completion. They not only approved the work, but also provided the support needed to complete the work in a relatively short period of time.

There were three main aspects of this effort: verifying previous peer reviews, obtaining the hundreds of high-resolution images, and determining any tunnel modifications or demolitions that have taken place in the interim. These tasks required the assistance of a myriad of people at NASA centers across the country. Steve Garber and Madelyn Pollack at NASA Headquarters were instrumental organizing the original peer review comments.

For the images, it was necessary to both determine their original identification number and ensure they were of sufficient quality. This massive undertaking was a collaborative effort with Teresa Hornbuckle at Langley, Elena Hunt and Donald Richey at Ames, Madison Teodo and Erik Conway at JPL, and Danielle Burleson and Jordan Whetstone at Marshall. In addition, Gerald Lee Pollard and Dr. William Devenport provided additional Langley images. Special thanks to Terry Hornbuckle, who doggedly tracked down over 300 images herself.

It was also necessary to have current technical experts add information on recent changes to the facilities. James Anderson and Rob Wyman provided vital contacts with subject matter experts at Ames and Langley, respectively. The Ames reviewers included Jon Bader, Jonathan Ikan, David Hash, Michael Wilder, Charles Cornelison, Brett Cruden, Maureen Delgado, Mike Ospring, and Frank Kmak. Reviews at Glenn came from Gwynn Severt, David Davis, Peter Struk, Andrew Broeren, Brian Willis, Jonathon Kubiak, Logan Micham, James Roeder, Dennis Eck, Taylor Varouh, Stephanie Simerly,

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PREFACE

Robert Arrighi

The wind tunnels of NASA and its predecessor organization, the NACA, are one of the most recognizable representations of the nation's aeronautics research. While the basic concept of blowing a gas through a duct and around a test object to determine the effects of that relative motion is easy to comprehend, at least in theory, few fathom the complexity of these facilities. Even seasoned engineers have a hard time grasping the sheer quantity, variety, and technical applications of these important facilities.

One of the first efforts to portray wind tunnel development from a historical, nontechnical viewpoint was William Corliss and Donald Baals's *Wind Tunnels of NASA* (NASA SP-440), published in 1981. This slim volume, which made no attempt to be comprehensive, has since been cited in numerous other histories and fulfills the promise laid out in its preface of going a "long way toward bridging the gap between engineer and layman."

Much has changed since 1981, however, including the expansion of NASA's History Program and the agency's concerted effort to remove its outdated or underused facilities, including many wind tunnels. These two events have overlapped to some degree with NASA's effort to meet its National Historic Preservation Act obligations by documenting the historic context of the facilities. As such, there are now Historic American Engineering Reports, websites, and books covering many specific facilities, including the Altitude Wind Tunnel and Full-Scale Tunnel. There remained, however, the lack of a comprehensive anthology of the NACA and NASA tunnels.

This project began in the early 2000s as NASA centers were beginning to formulate master plans that would result in the demolition of many of the agency's historic tunnels. Tina Norwood, then NASA's Federal Preservation Officer (FPO), approached NASA's History Office to sponsor an effort to update the Corliss and Baals book with descriptions of all current and former NACA and NASA tunnels. Whereas the original book wove descriptions of various tunnels into the overall narrative, the new publication would include encyclopedic entries for each facility with detailed physical and operational descriptions along with overviews of the research conducted.

NASA issued a request for proposals on 31 October 2005. J. Lawrence Lee, who had recently joined the National Park Service's Cultural Resources Program as an engineer-historian specializing in historic American engineering records, was selected for the project. Lee had previously published a number of papers on the history of technology and contributed to NASA's *The Wind and Beyond* series (NASA SP-2003-4409) of publications edited by James Hansen.

Lee visited the relevant NASA centers in 2006 and 2007 to tour many of the wind tunnels, interview those familiar with their operation and history, and gather pertinent documents and photographs. The resulting 750-page manuscript included detailed descriptions and, often rare, photographs of nearly 90 wind tunnels presented in a very readable and easy-to-understand writing style.

The manuscript went through the peer review process in 2010, with Lee making a number of revisions. The project then hit a snag regarding the formatting of the hundreds of images to be included in the text. With the contract funds depleted before editing or layout, the manuscript languished for years.

In the summer of 2022, Norwood, who by that time had moved on to serve as NASA's National Environmental Policy Act Manager, approached the History Office to initiate an effort to get the mostly completed manuscript published. The effort to publish was supported by the current FPO, Rebecca Klein. Chief Historian Brian Odom tapped Robert Arrighi, historian at Glenn Research Center, to manage the effort.

There were three main tasks to complete before editing and layout: verifying revisions from previous peer reviews, obtaining the hundreds of high-resolution images, and determining any tunnel modifications or demolitions that had taken place in the interim. For the images, it was necessary to both determine their original identification number and ensure they were of sufficient quality. Subject matter experts reviewed the technical data and provided updates on recent changes to the facilities. This work was primarily completed in late 2022 and early 2023 with the assistance of photo archivists, historians, engineers, and others from all the relevant NASA centers.

Although there are a multitude of wind tunnels at various organizations around the world, this book focuses strictly on the tunnels of the NACA and NASA. The majority of these facilities are or were located at Langley Research Center, Ames Research Center, and Glenn Research Center, although there have also been a small number of tunnels at Marshall Space Flight Center and the Jet Propulsion Laboratory. This book includes

tunnels with multiple test sections and those that have their own identity within larger facilities. Some, like the Unitary Plan Wind Tunnels, the Variable-Density Tunnel, and the Icing Research Tunnel, are well-known icons in the aeronautical community, while many others remain rather obscure, and a few are virtually unknown, even by many people at the NASA centers. Over the years, several were modified into tunnels with different characteristics and research capabilities, and often renamed. Arc jets and static test stands were not within the scope of the project.

The sponsors of this project expressed a desire that each tunnel be examined on an individual basis to be sure that no major facility was overlooked, and that each tunnel's unique significance, description, and history were clear. This led to an organization that allocates a listing to each facility and arranges those listings under their respective research centers. For context, each center's section begins with a brief history of that center. Since each of the NASA centers has had at least one comprehensive history published, readers are referred to them for additional information. In each research center section, the tunnels are, with some exceptions, presented in chronological order by their completion dates. Those that are part of a common facility, such as Langley's Hypersonic Facilities Complex, are grouped together. Most tunnels that were modified and renamed during their lives have all phases covered in a single listing, but a few cases that involved unusually large changes in design or role warranted separate listings for each phase. Prototype, or pilot, tunnels built to develop and/or validate certain design concepts inexpensively are usually discussed in the listing about the major tunnels they preceded, though some that also had significant research lives required their own listings.

Most of the images in this book came from NASA sources. Where they could be determined, the NACA or NASA image numbers are shown in the captions. An attribution to J. Lawrence Lee indicates either an original drawing or a drawing that is based on one or more NACA/NASA sketches or drawings, but it has been combined or altered to better illustrate a particular topic or feature. Figure numbers are provided for the images that were taken from technical publications or other reports without a drawing number.

Definitions of technical concepts or terms that apply to multiple facilities are discussed in one tunnel's listing, usually the earliest tunnel to feature that technology.

FOREWORD

Robert Pearce

Associate Administrator, Aeronautics Research Mission Directorate

The NACA and NASA have possessed more wind tunnels than any other agency, company, or university in the nation. The agency is currently constructing a new tunnel, the Flight Dynamics Research Facility, more than 100 years after its first tunnel was built in 1920. Although their role has evolved over the decades, wind tunnels continue to provide an essential tool for researchers studying aerodynamics, propulsion, and related topics. This publication provides the first comprehensive description of all (to the best of the author's knowledge) the NACA and NASA wind tunnels; from those with test sections just inches in diameter to the massive 80- by 120-foot section at the National Full-Scale Aerodynamics Complex; from those that operated only briefly to those that have been in service for decades; from those used to conduct esoteric basic research programs to those that contributed to the development of iconic U.S. aircraft and rockets.

This new version of *Wind Tunnels of the NACA and NASA* serves as a technical reference book for engineers, a documentary account for historians, and a comprehensive history for the general public. J. Lawrence Lee's work combines the technical information that often appears in facility catalogs with accessible writing and contextual information present in the original volume from 1981 and other historical narratives.

From Francis Wenham's first tunnel in 1870 to the present day, wind tunnels have filled a vital need in aerospace research. They have provided a safe, economical, accurate, controlled, repeatable, ground-based way for engineers and researchers to test and

evaluate a wide range of issues concerning the mechanics of compressible fluids and how they affect the design of objects like aircraft. No wind tunnel perfectly satisfies all of these requirements, but engineers gradually learned how to design and operate tunnels that minimized errors and produced increasingly reliable data. These data, generally consisting of aerodynamic forces in longitudinal, transverse, and vertical directions; moments about these three axes; static pressures at selected locations in the tunnel and on the test object; temperatures at selected locations; and visualizations using a variety of optical methods, compose a wind tunnel's "product." It is with this product that researchers and engineers can test their hypotheses, evaluate design ideas, and gain knowledge.

Wind tunnels were not the first machines used for aeronautical testing, nor are they the only means available today. Whirling arms, which rotated test objects in a circle, and flight-testing of models and full-scale aircraft have been useful in some circumstances, but both have drawbacks. The first rotation of a whirling arm moves the test object through relatively undisturbed air, but every rotation after that has the body moving through its own wake, making the results questionable. Although flight testing can produce excellent data, flying an untested aircraft has obvious cost and safety problems. Many new prototypes have crashed, and a number of test pilots have been injured or killed over the years. In recent decades, radio-controlled or automated models have reduced both cost and risk of the first flights of many experimental and concept planes. Full-scale flight testing is, of course, mandatory at some stage of an aircraft's development, but ground-based testing—primarily in wind tunnels—greatly reduces the unpredictability, risk, and duration of flight testing.

During the last half century, computational fluid dynamics (CFD), the mathematical modeling of fluid flows and forces, has become an essential tool for aeronautical investigation and design. Thanks to increasingly capable software and modern computers that can handle the complex calculations and gigabytes of data, CFD has substantially reduced the amount of physical testing performed, and as it continues to improve, that trend seems likely to continue. Nonetheless, physical testing continues to be an indispensable tool for verifying the computer modeling.

The number of NASA wind tunnels has been declining since the 1980s, as older and duplicative facilities were closed due to budgetary concerns and decreased demand stemming from the growth of computer modeling and military tunnels. At the turn of the century, the Rand Corporation assessed NASA's active wind tunnels and recommended that all but two be retained. Despite its maturity, the aircraft manufacturing industry still relied on NASA tunnels to verify CFD predictions and minimize costly flight testing. The report noted that even minor design inefficiencies can result in significant costs for the industry over time.

By that point, each of the remaining NASA tunnels was so unique that there were frequent backlogs of tests to be conducted, and reliance on foreign tunnels posed access and security issues. In the early 2000s, however, NASA was shifting large segments of

its aeronautics and science budgets to fund the new Constellation Program. In 2005, the U.S. House Subcommittee on Space and Aeronautics conducted hearings that examined the nation's long-term civil aviation research and development requirements. The subcommittee suggested that NASA deactivate and remove its underused and duplicative facilities, including wind tunnels. Thus began a long-term agency initiative to reduce its physical footprint, requiring that new construction be offset by a greater than equivalent amount of facility disposal. NASA has demolished more than two dozen tunnels since then, along with dozens of other facilities. The impact of this policy on national aeronautics research and development has yet to be determined. Ironically, this wave of destruction has led to increased historical documentation and a greater appreciation of the accomplishments of NASA's tunnels. In 1966 Congress enacted the National Historic Preservation Act to encourage the preservation of historic properties. Section 106 of the legislation requires that federal agencies assess the effect of their actions (including planned demolitions) on historic properties, and take steps to mitigate any adverse effects. These historic mitigation activities vary depending on the situation, but they often seek to tell the story of the historic structure that is altered or removed, providing historical context and discussion of its contribution to American history. NASA's Cultural Resources Management Program, managed by Rebecca Klein within the Mission Support Directorate, has been very active with historic mitigation in the 21st century. The result has been new websites, Historic American Engineering Reports, books, and exhibits describing many of these former facilities.

Although not originally planned as such, this new and expanded edition—*Wind Tunnels of the NACA and NASA*—contributes to the agency's historic mitigation efforts by providing descriptions—the only descriptions in some cases—of all of the former NACA and NASA wind tunnels, and by providing a discussion of the collective contributions of this property type to the aerospace field.

INTRODUCTION

J. Lawrence Lee

Hundreds of books have been written on aerospace topics. They cover virtually every kind of airplane, rotorcraft, lighter-than-air vehicle, and spacecraft yet built, plus a fair number of concepts that existed only on paper or in the mind's eye of both practical engineers and imaginative dreamers. Business and aviation historians have likewise produced additional books, papers, and journal articles about major and minor aircraft personalities and companies. Some have focused on the research facilities built and operated by the National Advisory Committee for Aeronautics (NACA), its successor the National Aeronautics and Space Administration (NASA), and institutions outside the United States. Many of these publications mention wind tunnels to a greater or lesser degree, but almost always in the context of an aircraft's development or as an incidental part of a manufacturer's or research institution's history. A number of textbooks and hundreds of technical papers on wind tunnels and wind tunnel testing have been written by and for engineers, but when this project commenced in 2005, few historians had ever delved into the history and development of wind tunnels as significant, useful, and interesting machines in their own right.[1] The most widely known of the few existing treatises is probably *Wind Tunnels of NASA* by Donald D. Baals and William R. Corliss, published in 1981 by NASA and long out of print, though accessible via the Internet.

During the writing of this book, however, there have been several histories written on specific NASA wind tunnels, including *Revolutionary Atmosphere: The Story of the Altitude Wind Tunnel and Space Power Chambers* (NASA SP-2010-4319, 2010),

Pursuit of Power: NASA's Propulsion Systems Laboratory No. 1 and 2 (NASA SP-2012-4548, 2012), and *Cave of the Winds: The Remarkable History of the Langley Full-Scale Wind Tunnel* (NASA SP-2014-614).

The topic is, admittedly, somewhat esoteric, but since 1871, when Francis Wenham designed, and he and John Browning built, a simple machine that is considered to be the world's first wind tunnel, hundreds more have been constructed worldwide. This first tunnel, built and operated for only a short time in Greenwich, England, bears little resemblance to modern examples in size, power, speed, accuracy, or complexity, all of which indicate a technology that has matured over time. Even a cursory look at the wind tunnels built since 1871 bears this out.

Europeans built a half-dozen tunnels before Albert Wells built America's first, primitive one at the Massachusetts Institute of Technology in 1896. After the Wright brothers achieved the first successful powered flight—with help from a wind tunnel—in 1903, European nations quickly dominated aviation research and development, including the construction of several noteworthy wind tunnels in the period leading up to World War I. Between 1903 and 1914, Europeans opened no fewer than 16 new tunnels, compared to only 3 in the United States.

Several years would elapse before the NACA opened its first wind tunnel in 1920 at the Langley Memorial Aeronautical Laboratory near Hampton, Virginia. Although the agency had a late start, the NACA's encouragement of brilliant engineers and the addition of new research laboratories and test facilities led to the organization's emergence as the world's premier aeronautical research organization. By 1958, the NACA had built more than 75 wind tunnels, including the three groundbreaking Unitary Plan Act tunnels in the 1950s.

The NACA's successor, NASA, changed many things about how this research was managed and focused, but dedicated researchers at the NASA centers continued to build, and glean extraordinary knowledge from, their wind tunnels to support both aeronautics and the growing field of astronautics. NASA built approximately 50 new tunnels between 1959 and 2000.

Like almost all technologies, the wind tunnel has had its own path of evolution. The primary path is fairly straightforward, but the story also includes branches off the main path to enable the investigation of specialty topics. Some of these specialty tunnels accomplished the tasks for which they were designed but did not spawn changes in the designs of other tunnels, yet others inaugurated features that influenced future tunnels as well. With one major exception, wind tunnel design evolution progressed essentially in step with progress in aircraft design. Both began as simple machines, but each stage of aircraft development raised new questions as performance envelopes expanded into previously unexplored realms of flight.

Successfully achieving greater speeds; higher altitudes; and larger, more-efficient airplanes demanded that engineers acquire greater knowledge about all aspects of aerodynamics and propulsion. While a debate over the benefits of theoretically versus

empirically derived knowledge flourished during the 1930s, the two fields ultimately came to reinforce each other and form a solid foundation for what became known as aeronautical—later aerospace—engineering. Data from testing validated or disproved the results of theoretical computations, and validated theory increasingly influenced aircraft and wind tunnel design.

All but a few of the tunnels built before World War II were subsonic, but their engineers employed a wide range of test section sizes and wind speeds to meet evolving needs. By World War II, a few tunnels were pushing Mach 1, the speed of sound, and tests in them revealed that conditions changed drastically near and above Mach 1. This stimulated the construction of supersonic tunnels during the 1940s and 1950s, just as turbojet engines and swept wings became dominant elements of airplane design.

German missile development during World War II led researchers there to build some of the earliest tunnels that approached hypersonic speeds. After the war's end, nations like the United States and the Soviet Union used this knowledge to build tunnels that could exceed Mach 5, the generally accepted minimum for hypersonic flight. Some exotic devices emerged in the late 1950s that used shock waves and free-flying models fired from guns in the opposite direction from the shocks to explore the hypersonic (above Mach 10) regime, speeds that have thus far been limited to space vehicles entering planets' atmospheres.

This capsule outline shows, as one might expect, that the speeds obtainable in wind tunnels increased over time in a more or less orderly fashion. (Similar trends exist for such topics as altitude simulation, instrumentation, and controls.) But, as noted above, there was one major exception to this trend. Pilots flying most of the early supersonic rocket and jet planes found their most unpredictable conditions and control difficulties occurred near Mach 1, a flight regime that was virtually impossible to reproduce on the ground. Below about Mach 0.7, subsonic wind tunnels performed admirably, and supersonic tunnels ran well above Mach 1.2, but what became known as the transonic range between these two speeds was fraught with problems. Subsonic tunnels "choked" as the air speed reached Mach 1 at any point around the model (with a general flow typically in the Mach 0.7–0.9 range, depending on the size of the model), and no amount of power could produce a higher speed. Supersonic tunnels became unstable as their speeds decreased below about Mach 1.2. Ray Wright, a researcher at the NACA's Langley Laboratory, is generally credited with developing a test section with slots that controlled the shock energy enough to enable stable transonic operation, though Wright built upon theory that was published during the 1920s. That theory suggested that carefully designed openings in the walls of a test section surrounded by a plenum could help control reflected shock waves and eliminate the choke point at Mach 1, but it was neither needed nor exploited until 1948, when Wright actually installed a slotted-wall test section in a wind tunnel. Slotted-wall test sections resolved the transonic testing problem at about the time it became clear from actual aircraft operations that most jet airplanes, particularly commercial transports, would cruise most economically at low-transonic

speeds. While both supersonic and hypersonic tunnels had preceded transonic ones, this unique departure from the expected incremental increases in speed over time was not due to a lack of interest in airflow around Mach 1, but rather to the complex nature of the transonic mix of subsonic and supersonic flows around an object. The transonic problem in wind tunnels was simply a tougher problem than those presented by supersonic and hypersonic speeds, and it took longer to solve.[2]

It is hoped that the reader will come to understand and appreciate not only these machines, but also something about the visions and thought processes of the many engineers who created them. To do so is to gain a better comprehension of how these extraordinary individuals visualized, defined, analyzed, and solved novel and increasingly complex problems. While they all had some knowledge base upon which to build, many of their designs for new tunnels involved new and untested concepts, or combinations of concepts, making those tunnels pioneering adventures as new airplane designs. In other cases, the same engineers designed eminently practical tunnels with few, if any, new features to efficiently handle a high volume of basic testing. All were products of their creators' sense of the organization's needs, resources, capabilities, and time constraints, and every tunnel discussed herein represents a unique set of trade-offs between these parameters.

That said, these engineers and researchers brought not only their intelligence and creativity to the centers; they brought their social backgrounds and individual personalities as well. There is, of course, no real separation between personal and professional lives, and their personal situations no doubt influenced their professional practice. A collective biography, however, is well beyond the scope of this work. Although much about some of these talented people has been recorded in a variety of formats, many volumes of biography still could, and should, be written to capture these fascinating characters.

Some analysts have predicted that computational fluid dynamics (CFD) will one day render wind tunnels completely obsolete. If so, that day has yet to appear on the horizon. Those developing CFD methods, including many NASA mathematicians and researchers, have made tremendous strides, and CFD is now a powerful, indispensable tool for aircraft and spacecraft design engineers. New CFD code, however, must be validated before it can be used, and some complex problems push beyond its current limits. In most of these cases, aeronautical researchers still look to wind tunnels for answers. Each new airplane design still endures many hours of testing and evaluation in wind tunnels before its first flight. To be safe and successful, aerospace engineers, like their counterparts in other engineering disciplines, must work with analytical theory that they know to be firmly grounded in reality. Although CFD has not eliminated wind tunnels, it has provided researchers and engineers with powerful tools that help them design ever-more-efficient test programs. By eliminating designs with clear deficiencies and indicating those with advantages, CFD helps engineers concentrate their testing resources more on design optimization than on early concept evaluation. This has

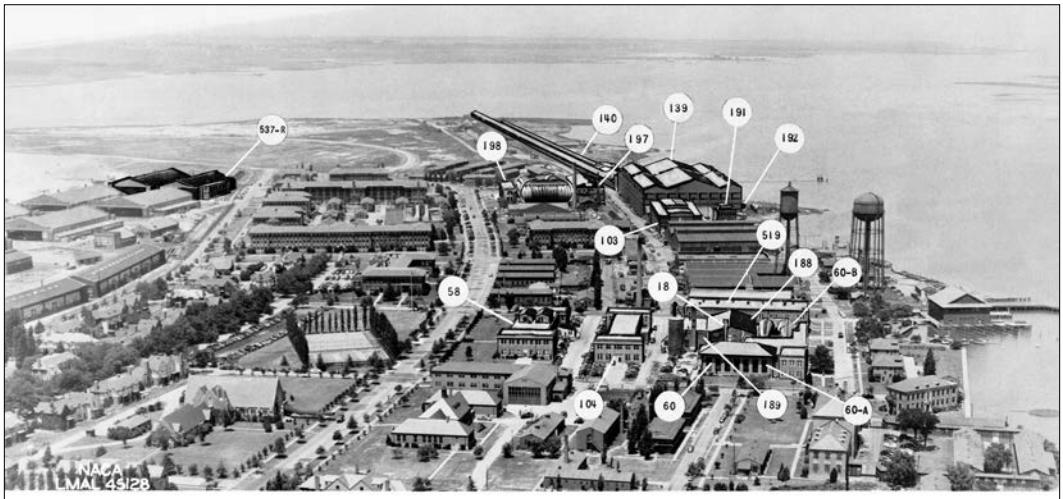
drastically reduced the number of hours that prototype designs spend in wind tunnels, but the hours now spent are much more focused and productive.

In addition to technological developments like CFD, changes in the aerospace industry, as well as in global political and economic conditions, have greatly reduced the number of manufacturers and new aircraft design projects. Accordingly, wind tunnel usage is now but a fraction of what it was when many of NASA's most-modern tunnels were built, and, as in many other businesses, wind tunnel testing is now a global market. Several European centers, some of which feature newer, more-modern tunnels, give NASA serious competition, and the remaining aerospace manufacturers have capable tunnels of their own for many applications. Coupled with the budgetary restraints of recent years, this situation has forced NASA to reexamine how wind tunnels and aeronautical research fit into its future. Without doubt, more existing tunnels, including a few with great historical significance, will meet the wrecking ball in years to come, just as many already have. But others continue to furnish avenues for the discovery of knowledge, and their future still appears reasonably bright. With well over a century of development and use, wind tunnels certainly represent a mature technology, but innovations in instrumentation and applications continue to appear, as do new aeronautical questions. If history is any guide, NASA researchers and engineers are not likely to lose their curiosity or their creativity in finding new ways to productively use these fascinating machines anytime soon.

ENDNOTES

1 An exception is William Leary's *"We Freeze to Please": A History of NASA's Icing Research Tunnel and the Quest for Flight Safety* (Washington, DC: NASA SP-2002-4226).

2 The various details of this general history outline are discussed at greater length in the sections that make up the bulk of this book. The references cited there informed this outline and need not be repeated here.



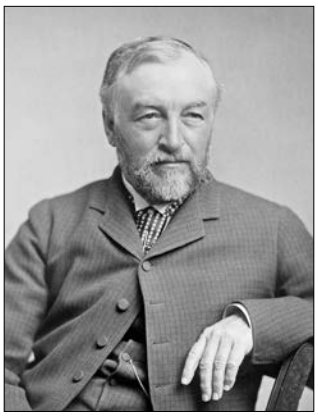
EAST AREA

58	Administration Building	198	19-Foot Pressure Tunnel
104	Service Building	60	Atmospheric Wind Tunnel
519	Utility Building	60-A	Rectangular High-Speed Tunnel
60-B	Two-Dimensional Low-Turbulence Pressure Tunnel	191	8-Foot High-Speed Tunnel
188	Two-Dimensional Low-Turbulence Tunnel	140	Tank No. 1
139	Full-Scale Tunnel	140	Tank No. 2
103	Propeller-Research Tunnel	140	Dynamic Model Shop
537-R	Flight Research Laboratory	192	East Substation
		18	24-Inch High-Speed Tunnel
		197	East Shop

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS
LANGLEY MEMORIAL AERONAUTICAL LABORATORY - LANGLEY FIELD, VA

This 1945 aerial view identifies the NACA's facilities in Langley's East Area. Although there were later facility changes, additions, and deletions, this was the maximum extent of East Area facilities. (Photo credit: NASA LRC-1945-B701_P-45128)

LANGLEY RESEARCH CENTER



Samuel P. Langley
(Photo credit: NASA LRC-1961-B701_P-06095)

When founded in 1915, the National Advisory Committee for Aeronautics (NACA) was charged to "supervise and direct the scientific study of the problems of flight, with a view to their practical solution,"[1] but Congress provided no funds to construct a laboratory for research on aeronautical problems until the next year. Initially, the committee had authority to use existing wind tunnels around the country, few though they were, but it soon became apparent that the NACA needed research facilities of its own. The NACA worked with the Army to find a site where they could share an airfield with space for a laboratory. They settled on a location near Hampton, Virginia, and construction at Langley Field began in April 1917, just as the United States entered World War I.[2]

Seeing the civilian NACA as moving too slowly to be of any use during World War I, the Army sought to solve its design, manufacturing, and operation problems by building its own research facilities at McCook Field in Dayton, Ohio. Army research personnel at Langley transferred to McCook, and the operations staff remaining at Langley gave the NACA little encouragement or assistance.

The NACA broke ground for the first office building at its Langley Memorial Aeronautical Laboratory (LMAL) in July 1917, but because of the Army's loss of interest and the steep learning curve confronting the NACA engineers, construction of its first wind tunnel did not start until spring 1919. The LMAL finally opened with a dedication ceremony on 11 June 1920. One of the speakers, Rear Admiral David Taylor, an American wind tunnel pioneer (and former opponent of the laboratory), was

effusive in his praise, proclaiming the new facility as "the shrine to which all visiting aeronautical engineers and scientists will be drawn."[3] Besides the office building, the fledgling LMAL consisted of an atmospheric wind tunnel, an engine dynamometer, a small warehouse, and 11 people.

Although the first wind tunnel at Taylor's "shrine," a 5-foot copy of an atmospheric tunnel at Britain's National Physical Laboratory, was obsolete when it opened, the tunnel gave the NACA researchers their first useful tool, and they wasted little time in inaugurating test programs and learning how to effectively use the tunnel. In 1920, a brilliant, but rather eccentric, German engineer named Max Munk arrived in America to join the NACA's staff. He brought with him an idea for a pressurized wind tunnel that would increase test Reynolds numbers to those generated in actual flight, and Langley's second tunnel, the Variable-Density Tunnel (VDT), was built to Munk's design. Work done in the VDT produced a catalog of airfoil data that thrust the laboratory into the forefront of aeronautical research facilities during the 1920s.

The LMAL grew substantially over the next decade, adding wind tunnels that set new standards in size and performance, including the 20-Foot Propeller Research Tunnel, the massive 30- by 60-Foot Full-Scale Tunnel, and the laboratory's first tunnels capable of Mach 1. These facilities occupied all the available land on the east side of Langley Field, so the NACA built its last pre–World War II wind tunnel, the 16-Foot High-Speed Tunnel, in a new area on the west side of the airfield. Most new tunnels opened after 1941were built in this West Area, and a few smaller ones were eventually relocated there as well. In 1948, the NACA shortened the laboratory's name to the Langley Aeronautical Laboratory (LAL), the same year that the laboratory's 8-Foot

This aerial view of Langley's West Area shows the campus around 1990. Most of the currently operating wind tunnels are located in the central cluster of buildings. (Photo credit: NASA LRC-1990-B701_P-07025)

High-Speed Tunnel began operating with a slotted-wall test section, making it the world's first wind tunnel to operate successfully in the transonic regime.

Driven by new jet and missile technology, plus the urgency of the Cold War, the LMAL grew rapidly after World War II. The new facilities that were opened during the 1950s included several supersonic and specialty tunnels, the Gas Dynamics Laboratory for hypersonic testing, and LAL's Unitary Plan Wind Tunnel, plus laboratories for investigating materials at high temperatures and instrumentation facilities.

When Congress created NASA in 1958, the NACA laboratories and staff formed its foundation, with the LAL becoming NASA's Langley Research Center (LaRC). Many of LaRC's activities became focused on human spaceflight as America embarked on the Mercury, Gemini, and Apollo programs that launched the first astronauts into space in 1961 and on to the Moon in 1969. NASA built new facilities at LaRC for astronaut training and the development of space navigation techniques, all of which performed essential roles in preparing for crewed space missions. The center continued to support the Space Shuttle with wind tunnels on standby and ready to investigate any aerodynamic problems that might arise during a mission, and as of 2023, LaRC personnel were performing test work on the Orion Crew Exploration Vehicle.

Budget limitations and changes in the aerospace industry have resulted in the closing of a number of LaRC's wind tunnels, the demolition of some, and plans to demolish others, including some with great historical significance. Nevertheless, the center continues to operate more than a dozen wind tunnels, and it remains America's largest, most comprehensive aeronautical laboratory.

An artistic rendering of Langley's new Flight Dynamics Research Facility, which is scheduled to begin operation in 2025. (Photo courtesy of BL Herbert International)

In August 2022, Langley broke ground for the Flight Dynamics Research Facility (FDRF), the agency's first major new wind tunnel since Langley's National Transonic Facility came online in 1982. The new 25,000-square-foot facility replaces two existing 1930s-era facilities, the historic 12-foot Low-Speed Tunnel and the 20-foot Vertical Spin Tunnel, which are located on the neighboring Langley Air Force Base. Both legacy tunnels are slated for demolition upon completion of the FDRF. The FDRF will be located on Langley's main campus near existing Buildings 1251 and 1208. The FDRF will provide researchers with a more versatile and robust test facility that is also more efficient to operate, is easier to maintain, and will provide high-fidelity data several times greater than that of the existing facilities. Construction of the FDRF is expected to be complete in 2025.

Wallops Flight Facility

The Wallops Flight Facility[4] began operation in 1945 as a satellite location of the Langley Laboratory operated by its newly formed Pilotless Aircraft Research Division (PARD). To explore high-speed flight, PARD was created to use rockets and drop tests to test free-flying models under conditions not then attainable in wind tunnels. For safety reasons, the rocket-launched tests had to be over the ocean, and the models were sacrificed into the sea at the end of each flight. Telemetry and radar systems developed by Langley's Instruments Research Division made it possible to collect much of the data measured in wind tunnels from the models during their brief flights. During the 1950s, many flights involved rocket-boosted ramjets, and the station built a preflight wind tunnel to test them on the ground before flight.

With the creation of NASA in 1958, the renamed Wallops Station became the launch site for early testing of the Mercury spacecraft and escape system, as well as the site for the development of tracking systems. Wallops also launched Scout and other sounding rockets on suborbital flights and ultimately small payloads into orbit. These activities expanded, and it became the Wallops Flight Center in 1975.

A reevaluation of facility roles by NASA in 1982 led the agency to place Wallops under Goddard Space Flight Center since its mission aligned more closely to that of Goddard. Renamed the Wallops Flight Facility, the station now serves as NASA's primary launch site for suborbital missions, many of which involve Earth resource studies.

The Preflight Jet Tunnel had been demolished before this 1962 image of the Wallops Flight Facility's "Launch Row" was made. The tunnel was located to the left of the main road, near its second curve in the upper center. (Photo credit: NASA LRC-1962-B701_P-00296)

ATMOSPHERIC WIND TUNNEL NO. 1

This 1921 photograph of the Atmospheric Wind Tunnel No. 1 shows its propeller and exhaust end. The test chamber is in the background, and the inlet (not visible) is beyond the test chamber. The drive shaft at right passes through a wall to reach the motor. (Photo credit: LRC-1921-B701_P-00004)

SIGNIFICANCE

The 5-Foot Atmospheric Wind Tunnel (AWT), also known as Wind Tunnel No. 1, was the first wind tunnel built and operated by the NACA at its new LMAL. Essentially a combination of existing design elements already proven in other tunnels, particularly those at Britain's National Physical Laboratory (NPL), the Massachusetts Institute of Technology (MIT), and Stanford University, the AWT broke no new ground in wind tunnel technology and was obsolete when it opened in 1920. Its greatest significance was that it gave the novice NACA engineers their first experience in designing, building, and operating a wind tunnel.

DESCRIPTION

Housed in a 92- by 43-foot rectangular brick building with a hipped roof and seven large windows in its long walls, the 47-foot, 2-inch-long AWT occupied the central portion of the building's main room. The venturi-type tunnel had a circular cross section throughout, including its closed test section, and it was built entirely of cypress. Supported by steel bents, the tunnel's centerline was 10 feet above the building's concrete floor. The AWT was an open-circuit tunnel, wherein its exhaust discharged into the main room, where it ultimately migrated back to the inlet. The interior walls of this

building (originally Building 60; now Building 580 in Langley's East Area) were made as smooth and free from obstructions as practical to avoid unnecessary disturbance of the return airflow.[5]

The tunnel featured a bell-mouthed inlet and, like the earlier Stanford Propeller Tunnel, a curved inlet section to gradually reduce the diameter from the inlet to the 5-foot-diameter test section, which was followed by a longer curved diffuser between the test section and fan. It was constructed with longitudinal strips of cypress that were carefully planed and sanded to yield the desired contour and smoothness. These strips were supported by a series of external rings, one-fourth of which rested on the steel bents. The inside of each hoop was circular, but its outside formed an octagon. Airflow was generated by a four-blade wooden propeller just inside the exhaust opening that was directly driven through a steel shaft by a 200-horsepower, variable-speed electric motor. The motor was mounted on a concrete pedestal in an adjoining room. The concrete foundation for the fan, shaft, and motor supports was separate from the foundation that supported the tunnel to minimize vibration transmission from the drive to the test section and balance. The building actually rested on a third, perimeter, foundation.

The AWT's test section, located approximately one-third of the way down the tunnel, was housed in an airtight chamber that surrounded that part of the tunnel. By isolating the tunnel from the outside room, it prevented air flows through small holes in the tunnel wall needed for model supports and instrumentation. An NPL six-component balance was mounted on the floor beneath the test section with its model-support probe extending upward into the tunnel. A second balance used multiple wires to connect the model to drag and lift scales mounted inside the chamber above the test section. Multiple manometers for measuring up to 18 pressures around the model were located in the lower part of the chamber, along with the motor start and stop controls. With its 5-foot-diameter test section, the AWT could test models with wingspans of up to 3.5 feet, about 5 percent of the span of a typical airplane of the day, without excessive wall-effect interference. To install and service these models, the test chamber had a large door, and the test section featured two sliding doors. When closed, these doors maintained the circular cross section of the tunnel to minimize disturbances. Two honeycomb flow straighteners, one just inside the inlet bell and the second immediately upstream of the test section, smoothed the incoming flow, and a simpler, cross-shaped straightener in the diffuser section helped prevent swirling motions induced by the fan from extending back into the test section.

HISTORY

Authorized in 1916 but delayed by World War I and the Army's changing priorities, construction of the AWT did not begin until spring 1919, though its design process started about a year earlier. During that time, the NACA's Frederick H. Norton and Edward P. Warner educated themselves about wind tunnels and developed a workable design. They started with a conservative tunnel that had five years of service, borrowed

elements from other successful tunnels, and then evaluated their design by building and testing a 1/5-scale pilot model (dismantled shortly after the AWT entered service). By war's end, the Army had become more cooperative at Langley Field, and the two engineers were close to finalizing the AWT's design drawings.[6]

Warner and Norton's starting point was the proven NPL-type tunnel. By 1918, the British laboratory had seven similar tunnels in service, ranging from 3 feet to 7 feet square in size, and Jerome C. Hunsaker (later a member of the NACA Main Committee) had built an almost identical one at MIT. It was a simple, open-circuit design with an induced-draft propeller fan and a constant cross section until just ahead of the fan. Its most complex part was an elaborate lattice distributor that quieted the exhaust air flowing back into the room. While a proven design, it already had been superseded by the venturi-type tunnels of Gustave Eiffel, Dimitri Riabouchinsky, and William Durand, not to mention Ludwig Prandtl's two closed-circuit tunnels in Germany.[7]

Warner and Norton were familiar with Durand's tunnel at Stanford University, since Durand was already running propeller tests there for the NACA. It was an Eiffel-type, open-circuit tunnel with an open-jet test section inside a closed chamber, tapered inlet and diffuser sections, and an induced-draft propeller fan. Its efficiency and airflow smoothness were both better than in the NPL tunnels, but its open jet was better suited to propeller testing than to wings or models of complete airplanes.[8]

Warner and Norton's design for the AWT combined the direct drive, rough proportions, and closed test section of the NPL design with the venturi and enclosed test chamber of Durand's tunnel. With an expanding diffuser to slow the exhaust air speed, and knowing that their tunnel would occupy a purpose-built building, they discarded the NPL tunnel's lattice distributor. Early operation demonstrated that some degree of exhaust control was needed, however, and a short, radial deflector was added outside the exit. The six-component balance developed by the NPL remained one of the best available, and they selected it for the AWT's primary balance. The NPL balance worked very well with relatively stiff models, but the NACA had begun to think about thin, internally braced wings and wanted to conduct tests of them as well. Such wings, especially when tapered from root to tip, were too flexible to be adequately supported by a spindle at one end of the wing attached to the balance's probe. For these tests, the engineers devised a balance that secured the airfoil models with wires. Its two scales, mounted above the test section, measured lift and drag forces.[9]

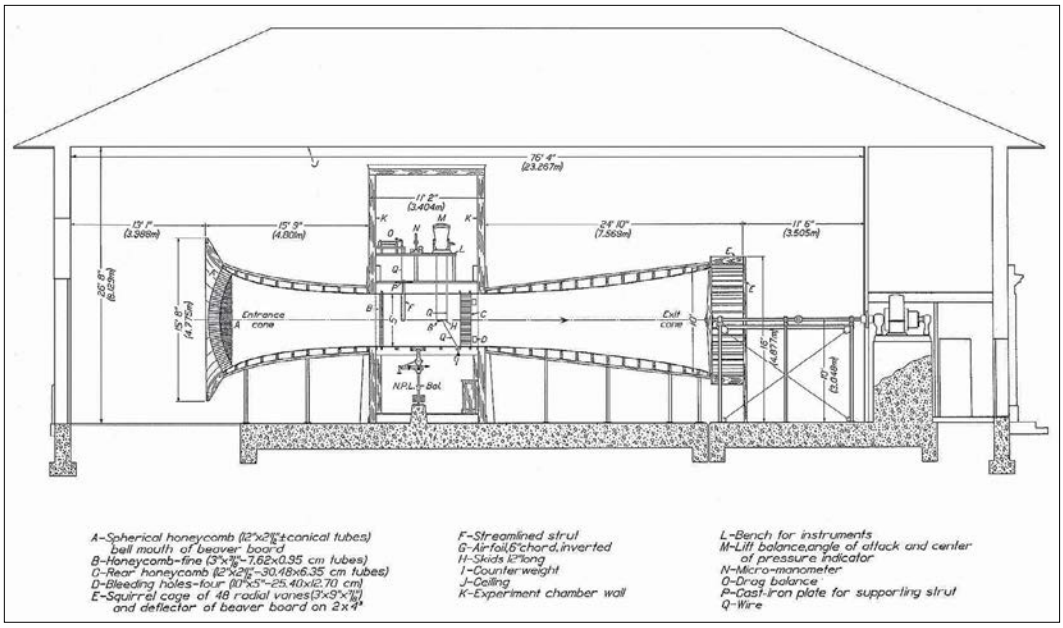
To obtain air speeds from 1 to 120 miles per hour (mph), the team chose a 200-horsepower, direct current (DC) electric motor. This variable-speed motor was mounted on a concrete pedestal in an adjoining room to reduce heat buildup in the main room. The massive pedestal minimized vibration transmission, and the motor, drive shaft, and propeller supports were separate from the tunnel support structure. With electricity scarce during Langley's early years, the DC power came from a generator driven by a Liberty aircraft engine in an adjacent building. To minimize heat generation in the test chamber, the motor-speed-control rheostats were located outside the chamber. Only the

motor start and stop push buttons were inside. Commercial power ultimately replaced the Liberty engine, but the controls remained unchanged during the AWT's lifetime.[10]

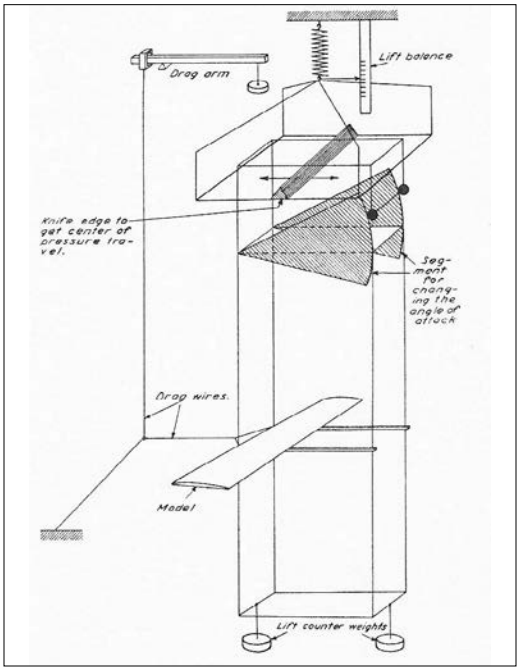
Although Warner and Norton rejected Durand's open test section, they recognized the value of the sealed experimental chamber around it. Bernoulli's Law meant that the static air pressure inside the test section would be significantly less than in the room outside. That differential pressure would force air through any hole or gap in the tunnel, and those jets of air could easily affect the tests. Sealing the test section and balance rooms inside a larger chamber would virtually eliminate such problems. It also isolated the balances from any effects of air moving through the main room. After calculating the likely operating conditions, the team designed the chamber's wooden walls, supported by four internal concrete columns, to withstand differential pressures of at least 80 pounds per square foot.

Once designed, the building and tunnel were erected in a little over a year and were ready for the laboratory's dedication on 11 June 1920. In truth, the new AWT was something less than state of the art, but the AWT finally gave NACA researchers a wind tunnel of their own, and they began to use it immediately. Unlike most of the country's few other tunnels, this one was intended for fundamental aeronautical research rather than military-driven problem solving. The desire to test thin, internally braced wings was one such area of interest, as was the effect of propeller slipstream on a wing's performance. Both programs required the development of unique machining, drive, and support devices to support the test operations, and that development began to build the NACA's strength in this vital realm.

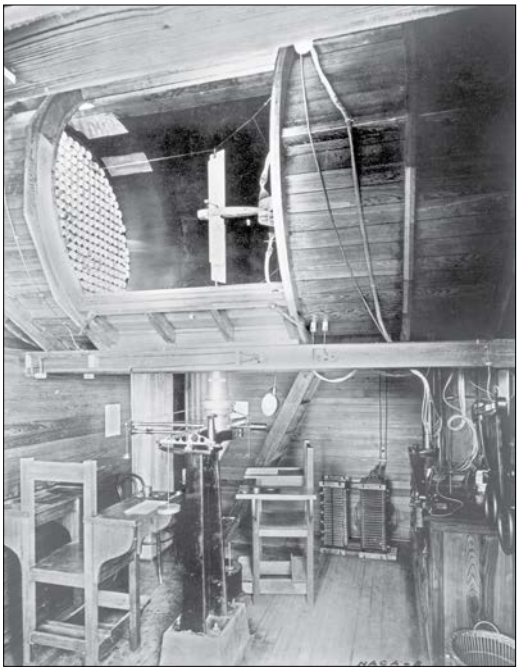
Wind tunnel technology advanced rapidly during the 1920s, and the AWT's usefulness declined, especially after the innovative Variable-Density Tunnel opened at LMAL in 1922. Within a decade, it was demolished to make room for two new tunnels, the 5-Foot Vertical Wind Tunnel in 1929 and the NACA's first 7- by 10-Foot Atmospheric Wind Tunnel a year later. Nothing of the original AWT remains, but Building 580 survives. The two "new" tunnels were dismantled after World War II, and a second floor was installed to convert the structure into an office building. Subsequently upgraded and modernized, it continues in that service for the Air Force.



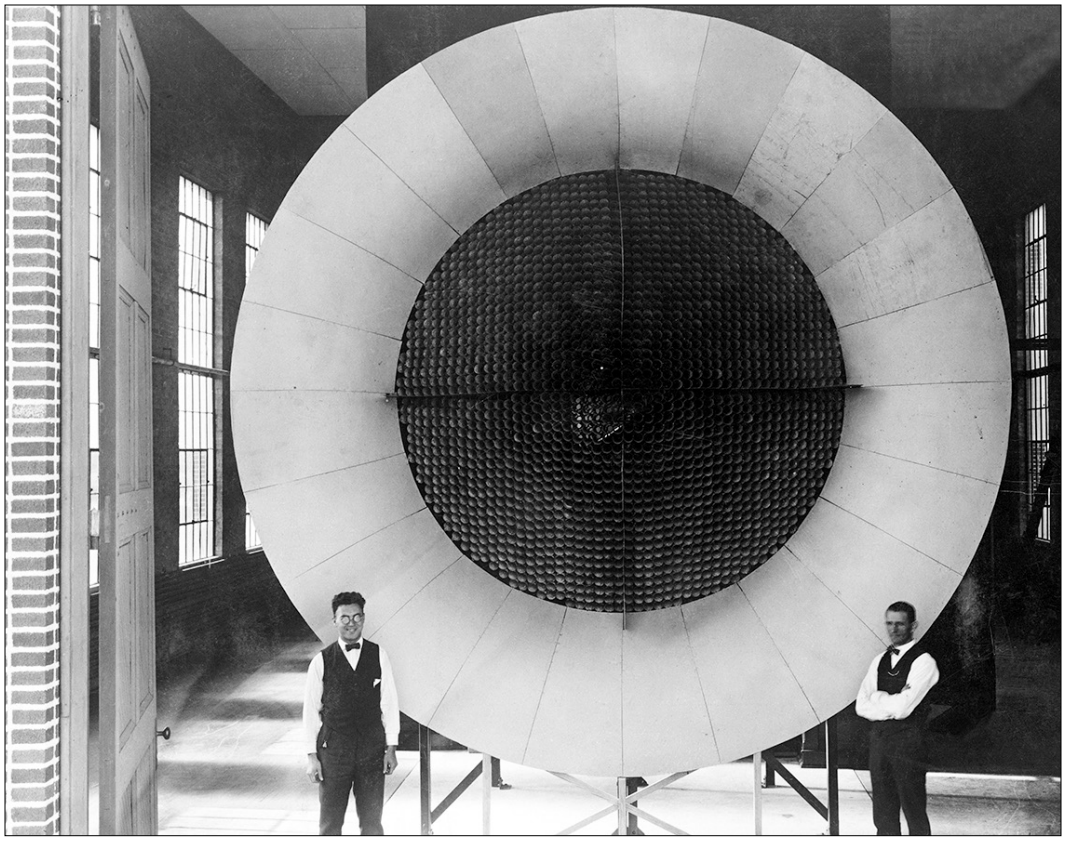
This section drawing of the Atmospheric Wind Tunnel in Building 60 (now 580) shows its major components. The NPL balance was mounted on a pedestal below the test section, while the scales for the wire-type balance occupied a part of the test chamber above it. Note the separate foundations for the tunnel and the fan and drive motor to minimize vibration in the test section. (Image credit: NACA Report No. 195, Fig. 1)



For airfoil studies in the Atmospheric Wind Tunnel, researchers found this wire-type balance more useful than the NPL balance used with most airplane models. The angle of attack was preset for each test run. (Image credit: *Journal of Society of Automotive Engineers*, vol. 8, Fig. 7)

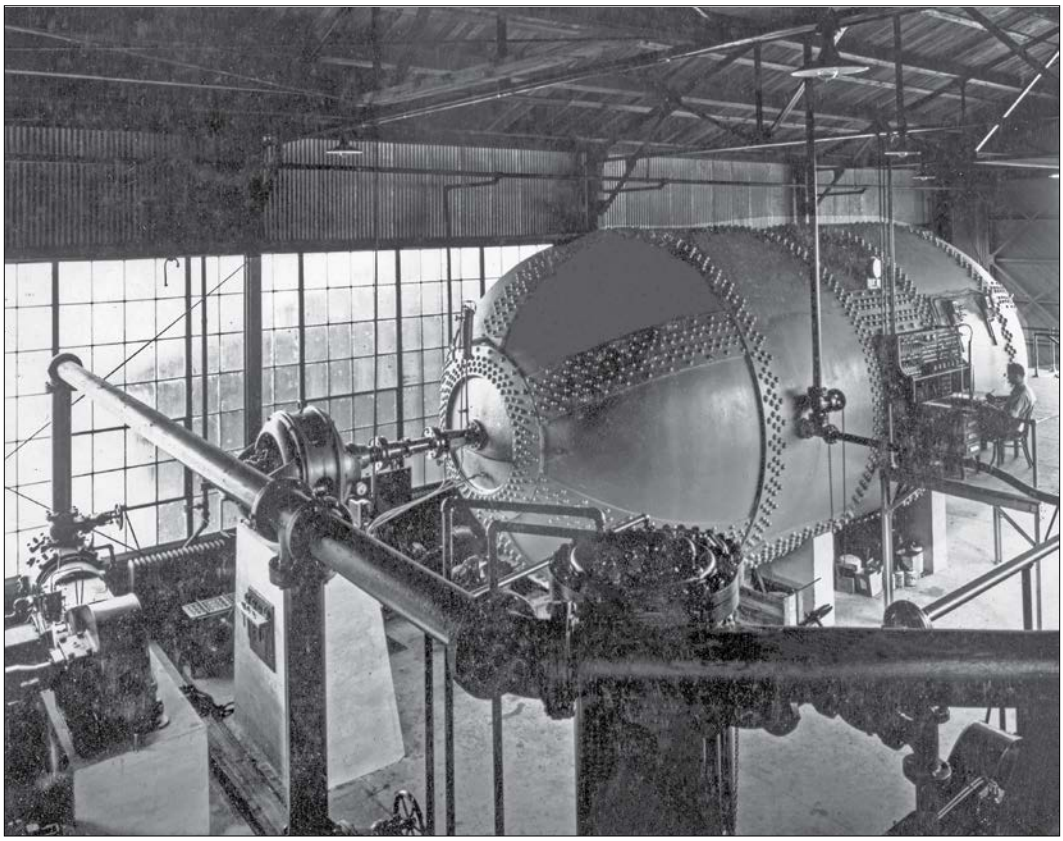


The Atmospheric Wind Tunnel's test section is seen here in 1921 with the NPL balance below it in the test chamber. An airplane model is mounted on the end of the balance's vertical support probe. Two researchers sitting in the unique chairs recorded data from the balance. Note the sliding test section door, the second honeycomb air straightener, and tubes from the model to manometers for static pressure measurements. (Photo credit: NASA LRC-1921-B701_P-00008)



This view of the Atmospheric Wind Tunnel's inlet shows its bell shape and the first of two honeycomb flow straighteners. The open building doors were closed during operation. (Photo credit: NASA LRC-1990-B701_P-04342)

VARIABLE-DENSITY TUNNEL



This 1923 exterior view of the Variable-Density Tunnel shows its drive motor at left, a portion of the air compressor piping in the foreground, and an operator seated at the control panel on the right. (Photo credit: NASA LRC-1923-B701_P-00463)

SIGNIFICANCE

The Variable-Density Tunnel (VDT) was the world's first wind tunnel designed and built to achieve near-flight Reynolds numbers by operating under pressure. It hosted a variety of test programs, including studies of several model airplanes to validate the high-pressure concept, but its most significant investigations involved airfoils. Through extensive use of the VDT, Max Munk, Elton Miller, and other NACA researchers developed accurate performance data for the commonly used airfoils of the era and then extended the investigation to develop families of airfoils with similar characteristics. *Technical Report 217*, "Preliminary Wing Model Tests in the Variable Density Wind Tunnel of the National Advisory Committee for Aeronautics," and *Technical Report 221*, "Model Tests with a Systematic Series of 27 Wing Sections at Full Reynolds Number," both published by the NACA in 1925, marked the start of a series of airfoil-design technical reports based on VDT tests. Additional programs added reliable data for dozens of additional airfoils to the aircraft designer's library. Even now, it is difficult to overstate the impact of these airfoil-test programs on aeronautical development.[11]

The VDT provided the unique capabilities needed for such a test program, and the airfoil data produced with it put the NACA and its Langley Laboratory "on the map" of first-class aeronautical laboratories in the mid-1920s. The VDT also served as the prototype for the many pressurized wind tunnels that have since been built. Accordingly, the VDT was designated a National Historic Landmark on 3 October 1985.

DESCRIPTION

The VDT originally consisted of a wooden, 5-foot-diameter, closed-circuit wind tunnel that was completely enclosed within a cylindrical, steel pressure vessel with hemispherical ends. Only this pressure vessel survives, the wind tunnel having been removed in the early 1940s. Built by the Newport News [Virginia] Shipbuilding and Dry Dock Company for service for conditions of up to 300 pounds per square inch (psi) pressure, the vessel measured 15 feet in diameter by 34 feet, 6 inches in length. Its cylindrical section consisted of three lapped courses of 2.125-inch rolled steel plate with battened butt joints. Joints were fastened with between three and six rows of rivets. Each end was assembled from seven pieces of 1.25-inch steel plate with battened butt joints fastened by six rows of rivets. The drive end included a shaft penetration and oil-sealed stuffing box that allowed the 7-foot-diameter internal fan to be driven at 900 revolutions per minute by an external, 250-horsepower synchronous electric motor. This induced-draft fan pulled air through the test section and diffuser and then blew it back to the other end through the annular return space. Neither the fan nor motor survive. The opposite end featured an elliptical plug door, 36 inches by 42 inches, that furnished access to the tunnel's test section for installing models and maintaining the balance. Several reinforced penetrations were provided for small observation windows, air piping connections, electrical wires, and instrumentation. At delivery, the vessel was stenciled as weighing 166,760 pounds.[12]

The tunnel's test section and induced-draft fan were along the shell's centerline, and the return flow passed through an annular space between the tunnel and shell. Because of space constraints, the 180-degree turns at each end were sharp and generated considerable turbulence, but the tunnel's speed was low (51 mph), and the designers felt the advantages from higher density would more than compensate for any turbulence problems. The tunnel itself was built of wood, and it originally featured a closed test section. A hatch at one end of the shell allowed access to the tunnel for model installation and tunnel maintenance.

The shell rested entirely above the floor on three reinforced-concrete pedestals. This required a mezzanine around part of the shell that served as a working platform. The control console was placed here, along with a large pressure gage just above it that indicated the pressure inside the shell. Three electrically driven compressors installed near the drive motor compressed the air inside the shell up to 20 atmospheres (300 psi), the amount calculated to offset a 1/20-scale model, a common size for use in 5-foot tunnels. Two 250-horsepower primary compressors filled the shell to approximately

7 atmospheres (100 psi). Higher pressures required additional compression through a 150-horsepower booster compressor.

Because the tunnel was sealed inside the pressure vessel, the balance assembly that measured forces and moments on the model was inaccessible during tests. Ordinarily, technicians adjusted the balances—each similar to a physician's scale—and took readings by hand, but this was not possible in the VDT, so the engineers devised a remote-control balance-adjusting system, the first of its kind, that allowed operators to bring each balance into equilibrium by positioning their weights from the control panel. Small electric motors turned camshafts to load gross weights on balance beams as needed, and other motors turned the lead screws to move the fine-adjustment weights along the beams. The operators engaged them while watching the scales through small viewing windows through the shell beside the control panel. Optionally, limit switches and revolution counters on the lag screws allowed the system to automatically bring itself into equilibrium. Once equilibrium had been achieved, operators read the forces measured by three scales. Models were secured to the balance using either wires or, more commonly, vertical struts. In both cases, the three-component balance yielded two forces (lift and drag) and one moment (pitch). A separate, remotely controlled motor and mechanism altered the model's angle of attack.[13]

HISTORY

The VDT, completed in 1922, became the facility that put the NACA "on the map," aeronautically speaking. It was the NACA's second wind tunnel, but whereas the first one had basically replicated a successful, but obsolete, earlier design developed at Britain's National Physical Laboratory, the VDT proved to be a substantial leap in aeronautical testing technology. It is best known for its use in a systematic series of tests that produced the NACA catalog of airfoils, the first set of reliable performance data for entire families of airfoils that designers and manufacturers could readily use to match airfoils to the needs of different aircraft.

Like other tunnels of the time, the NACA's Wind Tunnel No. 1, a 5-foot-diameter atmospheric tunnel, produced data using models that varied significantly from in-flight measurements on actual airplanes. To correct for this "scale effect," the difference in how a small model performs versus its full-size equivalent, German engineer Max Munk, who had recently immigrated to the United States to work for the NACA, proposed pressurizing the air inside a wind tunnel. While air molecules could not be "scaled down" in size like the model, pressurization would force them closer together to make the number of molecule-molecule and wing-molecule interactions approach that of the actual airplane in flight, thus generating similar airflows and lift/drag ratios. Munk based this idea on a formula developed in 1883 by Osbourne Reynolds, a British scientist trying to predict when fluid flow would change from laminar (smooth) to turbulent. Reynolds's formula computed a dimensionless number, later termed the Reynolds number, which allowed one parameter in a test, such as a model's length, to be traded

off against another parameter, like the fluid's density. Munk knew that pressurizing air increased its density, and he realized that greater density could be used to offset a model's smaller size. The key was to maintain the same Reynolds number, a condition known as *dynamic similarity*.[14]

Munk was not the only one with the idea to increase density. Wladimir Margoulis, a Russian-born scientist living in England, proposed using carbon dioxide, which has a density over one-and-one-half times that of air, in a closed tunnel at ambient pressure. Both concepts appeared at virtually the same time, and the NACA published technical notes describing both. The committee chose to pursue Munk's plan and built the Variable-Density Tunnel in a new corrugated metal building beside the brick structure that housed Wind Tunnel No. 1.[15]

Munk, assisted by NACA engineers Frederick Norton, David Bacon, and Smith DeFrance, designed a 5-foot-diameter wind tunnel that could be fully enclosed within a heavy pressure vessel (shell). Building 60-A (later renumbered 182), with a concrete floor, steel frame, and metal roof and siding, was built specifically to house the VDT. The pressure shell moved from the Newport News Shipbuilding and Dry Dock to Langley on a barge. After unloading, it was skidded from the Back River into position and jacked into place on its three pedestals. Langley woodworkers fabricated the actual tunnel inside the shell while pipe fitters and electricians installed and connected the air compressors and drive motor. The installation was completed in 1922.

Once the VDT was completed and calibrated to ascertain its performance parameters—primarily using simple shapes and airplane models—Munk and Miller began their famous series of tests to develop what became known as the "NACA airfoil catalog," though there was never a publication with that name. These tests replaced earlier, cut-and-try methods of airfoil design with a systematic procedure that began with a well-known airfoil and modified its geometry in carefully planned increments, thoroughly testing each one. The NACA published data for the first collection of related airfoils, which Munk named the "M series," as *Technical Report 221* in 1925. Subsequent test programs in the VDT and other Langley tunnels produced data for dozens of airfoils over the next decade. To better organize the various designs, researchers developed a four-digit numbering system, with each digit representing a specific airfoil parameter. By the mid-1930s, a five-digit series had also been developed. These data proved to be a crucial factor in what came to be called the "design revolution" of the 1930s.[16]

The VDT began operation as a closed-circuit tunnel with a closed test section, and it ran in that configuration for five years with no major problems. A broken light bulb changed all that in August 1927. Under a high internal pressure, with a correspondingly high partial pressure of oxygen, the wooden internal structure of the tunnel became quite flammable, and sparks from a light bulb that imploded under the pressure ignited it. The wood burned rapidly, destroying everything inside the pressure vessel. Having been built to boiler standards, the shell was not seriously damaged. The NACA rebuilt the VDT, but in a different configuration. To improve access to the balance and possibly

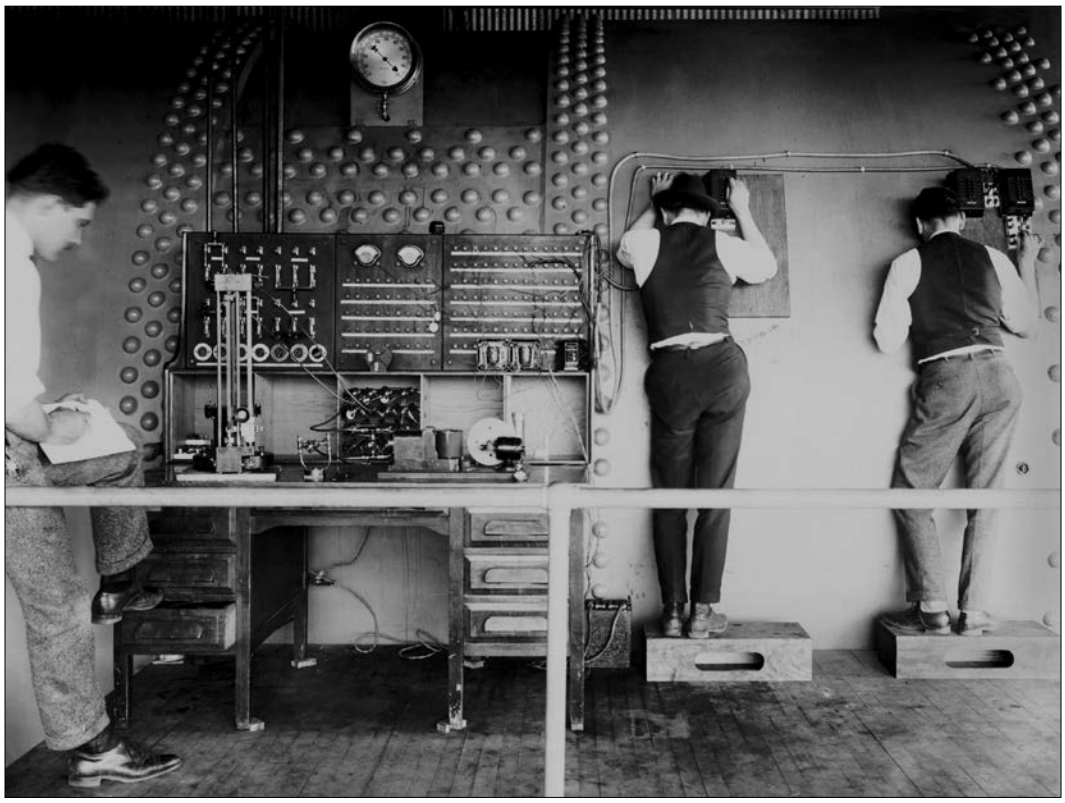
cure some of the VDT's infamous turbulence, the rebuilders tried an open test section and an inlet nozzle having greater constriction. This proved to be unsuccessful, and the VDT underwent another rebuilding in 1930 to reinstall a closed test section.[17]

The VDT also offered NACA researchers an opportunity to run their first high-speed tests. The 5,200 cubic feet of 300-pound-square-inch air still inside the shell after each VDT test represented a large amount of stored energy that John Stack and George Lewis realized could power a small blowdown tunnel. In the 11-Inch High-Speed Tunnel, built in 1928, this high-pressure air was injected into an annular nozzle that exhausted to the atmosphere. Its high velocity produced a partial vacuum in the nozzle throat that induced a larger amount of room air to also flow through the nozzle's throat at a high velocity—up to the speed of sound. Here Stack and Eastman Jacobs did their earliest high-speed research. This tunnel was so successful that it was replaced with the 24-Inch High-Speed Tunnel, similarly powered by VDT air, in 1934.[18]

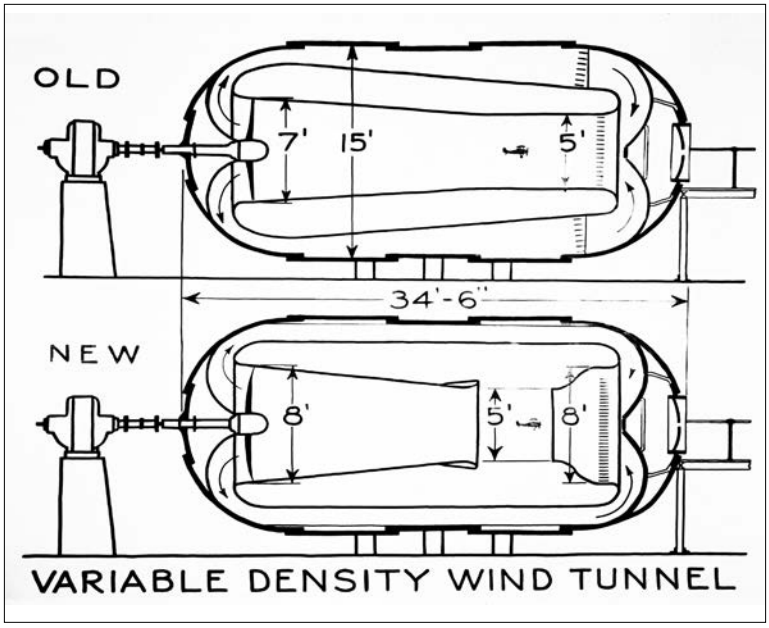
The VDT remained in service for a decade following its 1930 rebuilding, but it took on a different role after 1941. To economize on construction of its new Low-Turbulence Pressure Tunnel, Langley decided to remove the old tunnel and use the VDT's air compressors (later replaced) and pressure vessel to supply 150-pound-per-square-inch air to the new tunnel, a service this equipment rendered for another four decades. Though the vessel had never experienced structural problems, its age and riveted construction increasingly concerned safety engineers, and they decided to retire it in 1981. Recognizing the historical significance of the VDT, Langley removed it from Building 582 (previously designated as Building 60A) and relocated the VDT as a landmark display beside the center's Henry J. E. Reid Conference Center in the West Area in 1983, where it rested on concrete pedestals similar to those that originally supported it. The National Park Service designated it a National Historic Landmark on 3 October 1985.

In 2019, when the Reid Conference Center was demolished, the VDT was again relocated, this time next to the newly constructed Integrated Engineering Services Building (Building 2102) at the center of Langley's campus.

The VDT pressure vessel has since been designated as Building 1226.



The Variable-Density Tunnel was controlled from this panel on an elevated platform. Note the all-important pressure gage above the panel and the technicians peering through portholes at the model inside in 1923. The pressure shell's riveted construction is clearly evident. (Photo credit: NASA LRC-1923-B701_P-00484)



These section drawings show the Variable-Density Tunnel with closed (top) and open (bottom) test sections. It was built with a closed test section. The open test section installed after the 1927 fire proved to be unsuccessful, and the original design was replicated in 1930. (Image credit: NASA LRC-1928-B701_P-02929)

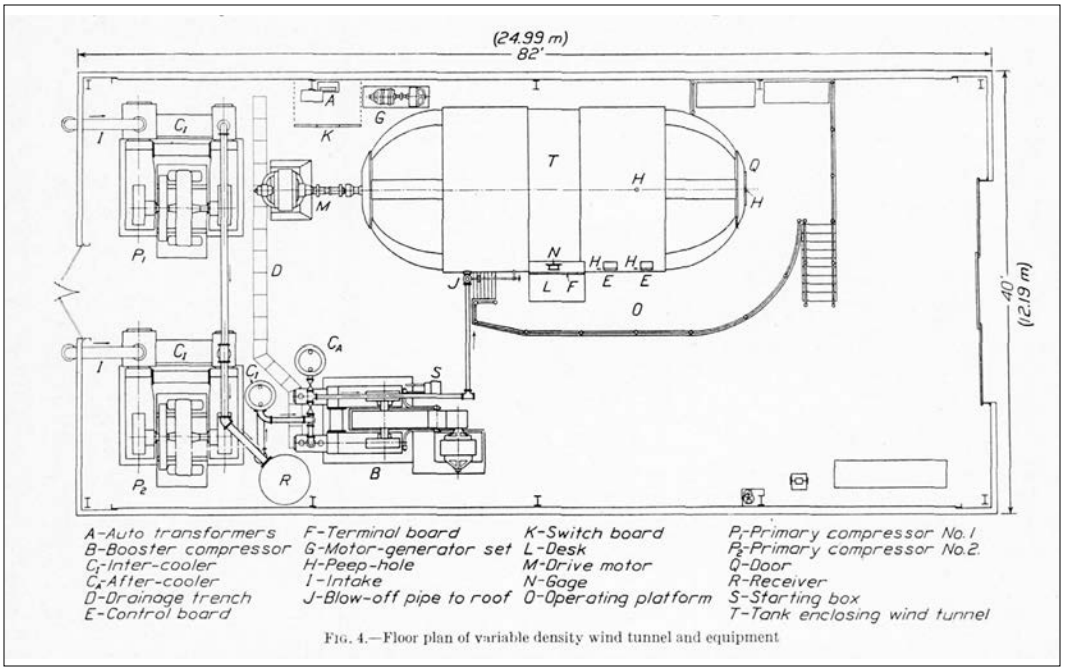
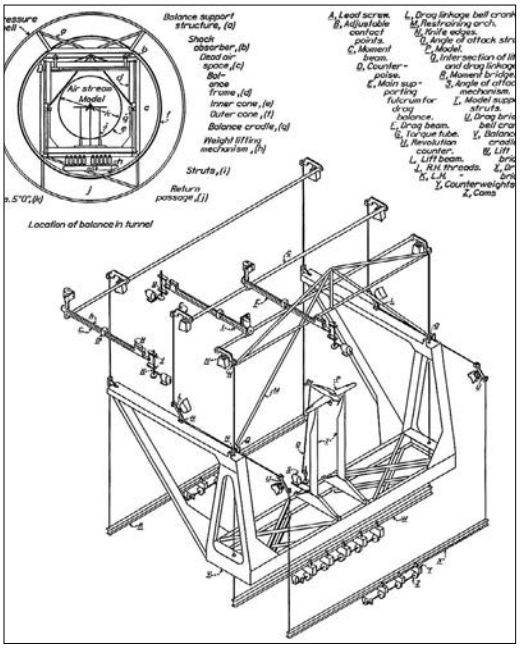
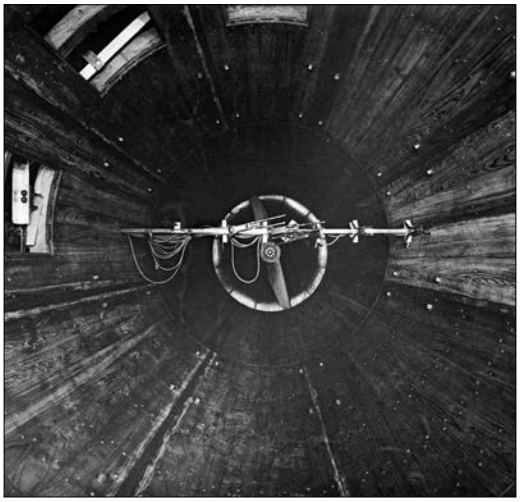


FIG. 4.—Floor plan of variable density wind tunnel and equipment

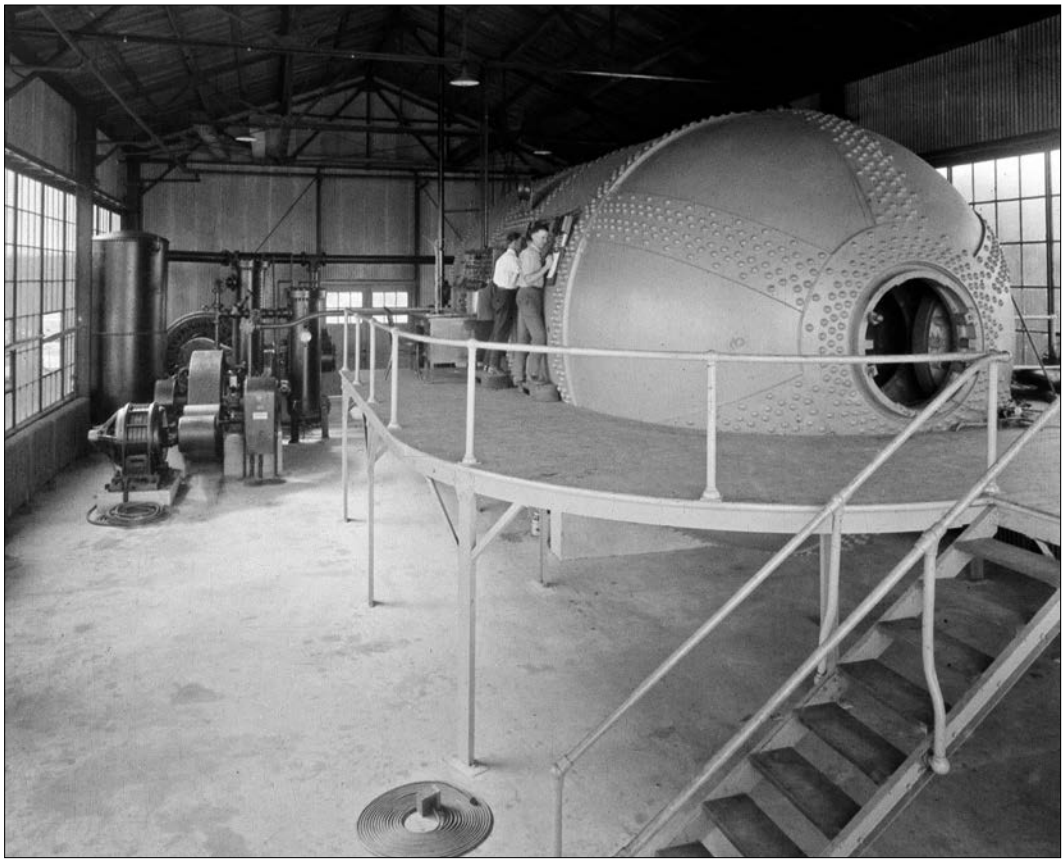
This floor plan drawing of Building 60-A shows the layout of the Variable-Density Tunnel and all of its supporting equipment. (Image credit: NACA TR-227, Fig. 4)



Since the actual wind tunnel was sealed inside the Variable-Density Tunnel's pressure shell, Langley engineers built this novel balance that used several small electric motors to automatically adjust the weights on the balance beams while the test run was in progress. After it completed its balancing cycle, technicians looked through the portholes to read the setting on each scale. (Image credit: NACA Report No 416, Fig. 5)



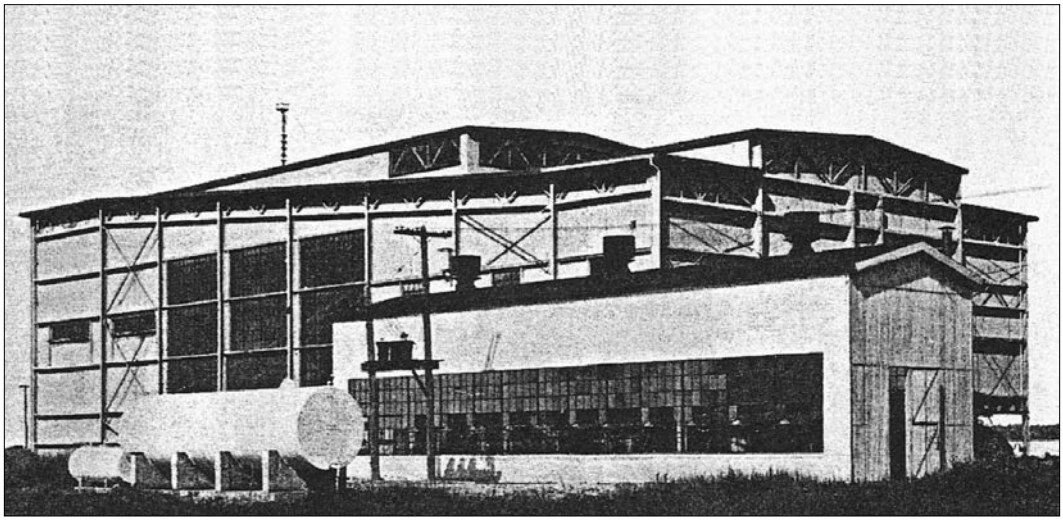
This interior view of the Variable-Density Tunnel, taken shortly after it opened in 1922, looks downstream. Note the wooden construction, the propeller in the background, and the observation windows. These windows aligned with small portholes in the pressure shell. (Photo credit: LRC-1922-B701_P-00405)



This 1923 view of the Variable-Density Tunnel shows its access door open at right and one of the air compressors in the left background. For several years, Building 60-A had the corrugated iron siding visible here. Although the steel structure stayed in place, the siding was replaced with brick when this area was joined to the new Building 60-B (now 582-A), constructed to support the Low-Turbulence Pressure Tunnel. (Photo credit: NASA LRC-1923-B701_P-00460)

The Variable-Density Tunnel's pressure shell is now on display near the Henry J. E. Reid Conference Center in the West Area. The National Park Service designated the VDT a National Historic Landmark in 1985. (Photo credit: NASA LRC-2019-B701_P-00409)

PROPELLER RESEARCH TUNNEL



A general view of the Propeller Research Tunnel in the 1920s. The engine house in the right foreground enclosed two 1,000-horsepower diesel engines that first powered the tunnel. They were later replaced with electric motors after adequate power became available. (Photo credit: NACA Report No 300, Fig. 2)

SIGNIFICANCE

The Propeller Research Tunnel (PRT), completed in 1927, was the first wind tunnel large enough to test an actual single-engine-aircraft fuselage, engine, and propeller. It enabled accurate, full-scale testing of propellers, which had proven impossible to evaluate outside of expensive and time-consuming flight tests. The PRT's large size made it a challenge to design and build, but that size allowed full-scale aerodynamic testing of engines and propellers, plus other aircraft components as well, including landing gears, tail designs, and engine cowlings. The renowned NACA cowling, for which the organization received its first Collier Trophy in 1929, was developed and refined through tests in the PRT. Because of its size, the PRT was the NACA's first wind tunnel to be designed as a complete structure rather than as a machine located inside a building. This tunnel demonstrated the practicality of large-size wind tunnels and served as the prototype for other large tunnels constructed by the NACA and others.

DESCRIPTION

Externally, the PRT appeared to be a large industrial building, 166 feet long, 89 feet wide, and a maximum of 56 feet high. It utilized a riveted, structural steel frame, to which 2- by 6-inch tongue-and-groove pine sheathing was attached with wooden nailers. Since the exterior walls also served as outer walls of the tunnel's return passages, they were fastened to the inside of the steel frame. Large windows made up most of the central three panels (out of eight) that made up the long walls. The roof, supported by internal,

Warren steel trusses, was in four sections, with two slightly pitched central sections and two sloping portions over the long walls.[19]

An 84- by 20-foot building at the tunnel's southwest corner housed the PRT's original drive, a pair of 1,000-horsepower diesel engines. These engines were mounted end-to-end, and drive belts transmitted their power to the fan shaft. The 55-foot-long belt system was enclosed within a trapezoidal housing on the tunnel's south end.

The PRT was a closed-circuit, open-throat tunnel with dual return ducts. The open test section was located in the center of the structure, and the two return ducts made up its perimeter. Throughout, the tunnel's centerline was 25 feet above the concrete floor. The 35-foot-long test section consisted of the open area between the 20-foot-diameter entrance cone and 33-foot-diameter exit cone. An open jet of air passed between the two cones and around the model, often an actual airplane, mounted on a balance stand. This was contained within a 60- by 50- by 55-foot test chamber that acted like an Eiffel-type experimental chamber to isolate the test section from the rest of the tunnel's airflow. The exit cone, which captured the air jet, quickly curved down to 25 feet in diameter, then began a gradual enlargement through the return duct. The 28-foot-diameter, 8-blade propeller was mounted 35 feet beyond the exit cone on a shaft with an aerodynamic fairing. It propelled the air toward the south wall, where two pairs of 90-degree turns equipped with airfoil turning vanes split the airflow and sent it back north through the two return circuits. Still gradually increasing in size, these ducts were rectangular. At the north end, two more pairs of 90-degree turns, also with turning vanes, merged the air back into a single flow in the tunnel's 50- by 20- by 50-foot settling chamber. A symmetrical transition reduced this to 20 feet in diameter at the entrance cone, where the air again flowed through the test section. As with the exterior walls, the inner portions of the return ducts and the two cones were made of wood. Large windows in the inner walls opposite those in the outside walls admitted considerable natural light into the test chamber. Both the inner and outer walls of the west side return duct featured large doors to provide access to the test chamber for test objects and equipment.

A large steel stand supported the test model, which was often an actual airplane, at the tunnel's centerline, usually at the plane's two landing wheels and tail skid. This triangular stand rested on three beam scales, and a fourth scale was attached to both it and a counterweight. Together, these four scales furnished data from which the aerodynamic drag and propeller thrust forces could be computed. For tests requiring the measurement of engine power, a torque dynamometer replaced a test airplane on the balance. Built of structural steel and shaped like a Vought VE-7 aircraft fuselage, any engine-propeller combination could be mounted on it so that a dial-type scale in the aft cockpit displayed the engine's torque in foot-pounds. Power could easily be calculated from this and the engine's speed. Although other engines could be mounted for testing, a Wright E-2 engine served as the baseline powerplant for tests of most new propeller designs. The dynamometer's frame was covered in a combination of sheet metal and doped canvas that emulated an actual VE-7's fuselage.

HISTORY

By 1925, the work of Max Munk and Elton Miller in the Variable-Density Tunnel had produced the first of several sets of performance data and design ratios for families of airfoils. Since the pressurized VDT generated high Reynolds numbers, these data correlated well to full-size airfoils, and aircraft designers quickly embraced them. Similar tests for propellers, which are actually rotating wings, failed miserably for three main reasons. The rotary motion meant that every part of the blade (wing) had a different speed through the air. Full-size blades also flexed under load in both bending and twisting modes. Models could not replicate this flexure, nor could they generate the compressibility effects real propellers experienced at their tips, so they produced largely worthless data. A young Navy engineer, Fred Weick, had wrestled with these problems, but no existing tunnel could accommodate the real propellers he wanted to test.

Following correspondence with Weick and others about research needs, NACA Director of Research George W. Lewis began to wonder if a tunnel large enough for the tests Weick suggested was possible, and he discussed it with Max M. Munk, the quixotic German emigrant who had proposed the VDT. Munk thought such a tunnel was possible, so Lewis invited Weick to join the Langley staff and help design, build, and then run it. Weick agreed, and Lewis authorized the project in 1925.

Weick had already done some calculations that roughly defined the new tunnel. To test a 10-foot propeller, he felt the tunnel needed a 20-foot-diameter throat and a speed of at least 100 mph. This would require about 2,000 horsepower, about 10 times that of Langley's other two tunnels. Engineers Elton Miller and Donald Wood worked with Weick to design the PRT, though as Langley's chief of aerodynamics, Munk insisted on approving every detail, a source of great friction due of his unpredictable nature.[20]

While the PRT was large, its basic configuration was not too difficult to design. Using dual return ducts kept the size of each one and the overall structural framework reasonable, and the largely wood construction, even of the tunnel's most complex contours, was well within the capabilities of local craftsmen. The biggest hurdle to overcome was power. That much electrical power was not available from Langley Field or the city of Hampton at the time, so an alternative power source had to be located. It was found in the form of two Nelseco (a trade name used by New London Ship & Engine Company) 6-cylinder diesel engines that the navy had salvaged from a problematic submarine, the U.S.S. T-2. These engines were mounted end-to-end, with their crankshafts joined by a 44-groove sheave. Power transmission was through 44 "Texrope" V-belts to an identical sheave on the fan shaft, with belt tension maintained using two adjustable idler sheaves. Each engine produced 1,000 horsepower at 375 revolutions per minute. These diesel engines remained in service until 1933, when adequate electrical power allowed their replacement by an electric motor.[21]

Unlike the smaller tunnels, the PRT required a completely new type of balance that could accommodate a complete airplane. Weick designed the balance to use four beam-type platform scales. Although maintained in position by a fixed steel structure,

the weight of the balance and model, plus forces from aerodynamic loads, all bore directly down onto three of these scales. Simple arithmetical calculations using the scale readings yielded the needed aerodynamic forces and moments on the model. A fourth scale, linked to the balance frame and a counterweight, measured the thrust produced by the propeller. A technician at each scale simultaneously recorded the data at periodic intervals. Most engine-propeller tests required a "pilot" in the cockpit to operate the engine and also read the torque scale when the dynamometer was used. He climbed into and out of the cockpit using a portable ladder.[22]

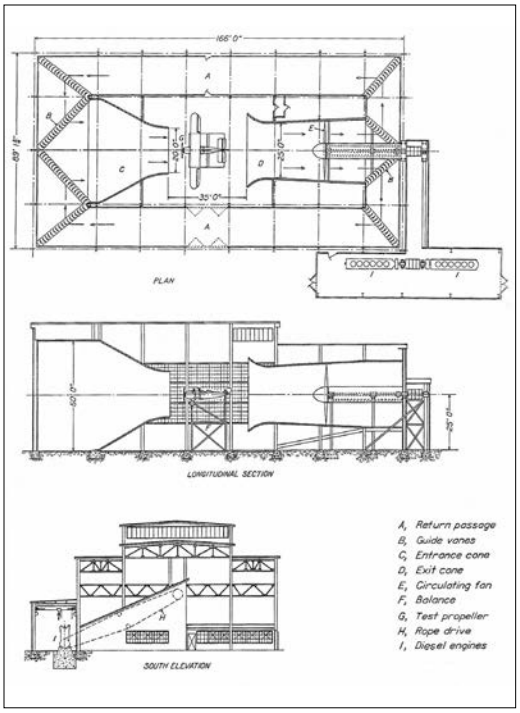
Starting the test engine presented another problem. Engines of the era were usually started by pulling on the propeller. While a burly technician on a ladder accomplished this for the first few runs, it was an obviously unsafe and impractical task with a propeller 25 feet above the floor. The team built an electric starter that attached to the entrance cone. A chain from the motor turned a hollow tube that engaged the propeller. Once the engine started, the apparatus could be rotated out of the airstream.

Entering service in July 1927, the PRT soon began producing useful data and encouraging the development of new research techniques. One of these techniques was an optical method to measure the blade deflection of a spinning propeller. A telescope was mounted below the propeller looking up at a black panel on the ceiling, and one of the propeller's blades was painted black as well. Two lights were directed at the propeller. In operation the black blade's passage would not be seen through the telescope, but the light reflected off the other blade's edges could be seen. The amount of movement was measured using the telescope's cross hairs, and this could be used to calculate the angular deflection at any point along the blade.[23]

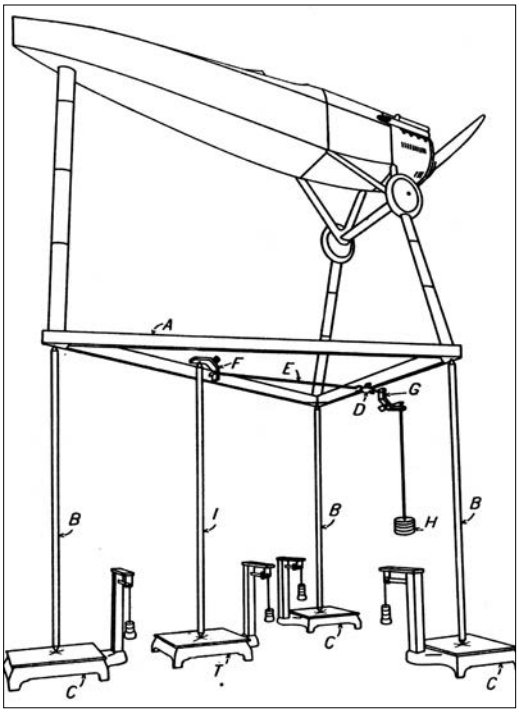
As noted above, probably the most significant program to utilize the PRT was one to investigate ways to reduce the aerodynamic drag of radial engines. The Navy, Weick's former employer, preferred air-cooled radial engines because they caused fewer maintenance problems aboard ship than water-cooled in-line engines, but they had high drag penalties from the finned cylinders that stuck out into the airstream. Upon request, the PRT Section began an investigation to see if drag could be reduced without cooling impairment. Weick began a systematic investigation in the PRT that ultimately produced surprising results. Within a year, his team had produced a cowling that completely surrounded the engine. Cooling air entered an opening around the propeller shaft and exited through a circumferential slot behind the engine. Internal baffles directed the flow around the cylinders. It performed far better than expected, reducing engine drag by a factor of three. In flight tests, two different airplanes with the new cowlings saw 13- and 16-percent increases in their top speeds. The drag reduction could also be realized as greater fuel economy and range. Recognizing the importance of the cowling, the National Aeronautic Association presented the NACA with its Collier Trophy, America's highest aeronautical achievement award, in 1929. It was the first of several that Langley research would earn.[24]

Other test programs in the PRT used scale models, but they could be larger than those for other tunnels. In the 1930s, as larger planes using multiple engines became more common, the PRT Section began investigating whether engine location on a wing made any significant difference. Tests using a wing section and two engines proved that it did. Earlier multi-engine airplanes mounted engines entirely away from their wings, but PRT tests revealed that mounting them on the wing's leading edge in a streamlined nacelle provided both propulsion and drag enhancements. Most large aircraft built after 1930 used this arrangement.[25]

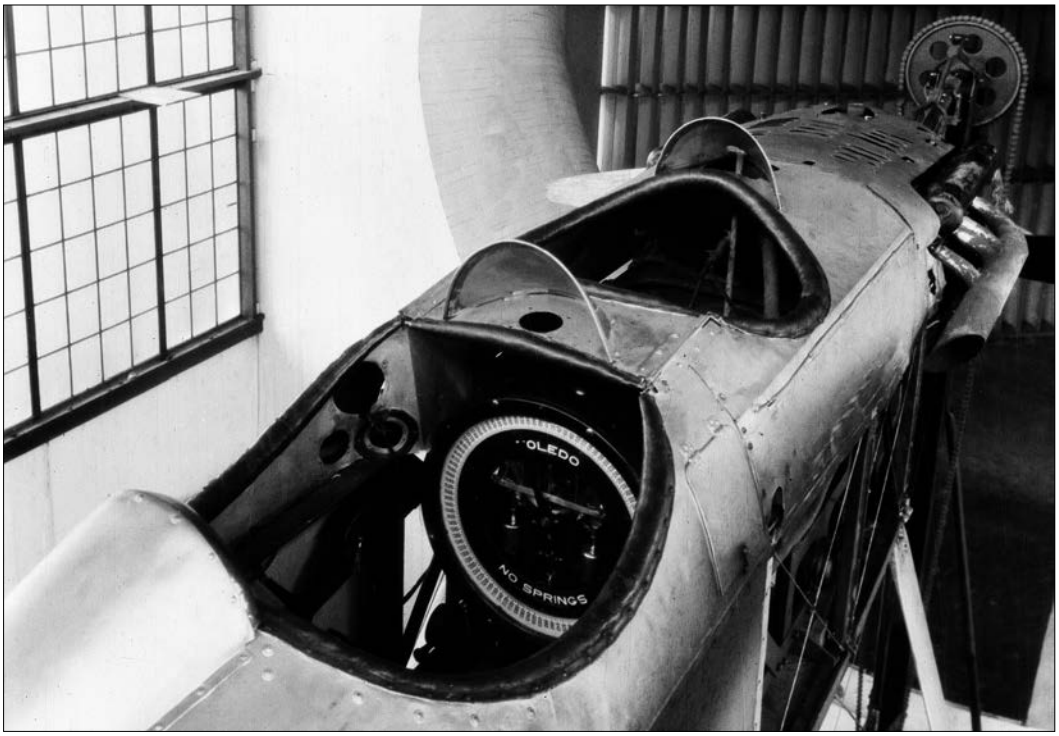
The PRT's success spawned a larger wind tunnel at Langley, the 30- by 60-Foot Full-Scale Tunnel, and an even larger 40- by 80-foot one at the Ames Laboratory in California. These tunnels were able to accommodate larger airplanes, wings and all, and the PRT's research load dropped, especially after World War II and the introduction of jets. Unable to contribute anything toward solving the new problems of the jet age, the PRT was dismantled in 1950 to provide room for Langley's new 8-Foot Transonic Pressure Tunnel.



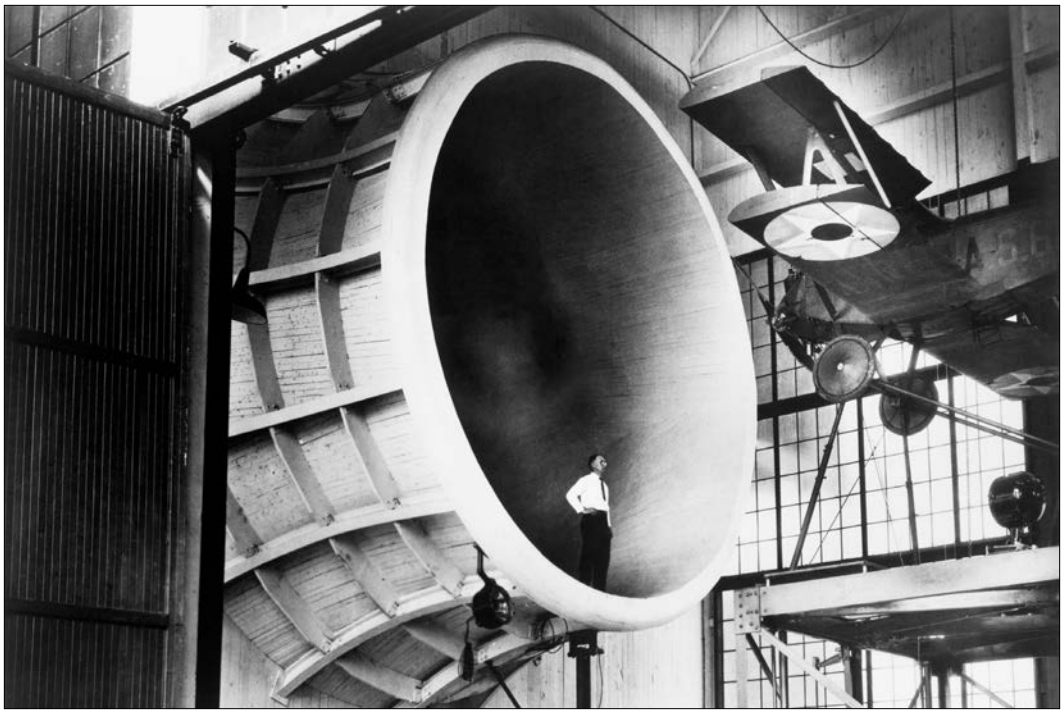
These plan and section drawings of the Propeller Research Tunnel as originally built show its general arrangement and major components. (Image credit: NACA Report No. 300, Fig. 1)



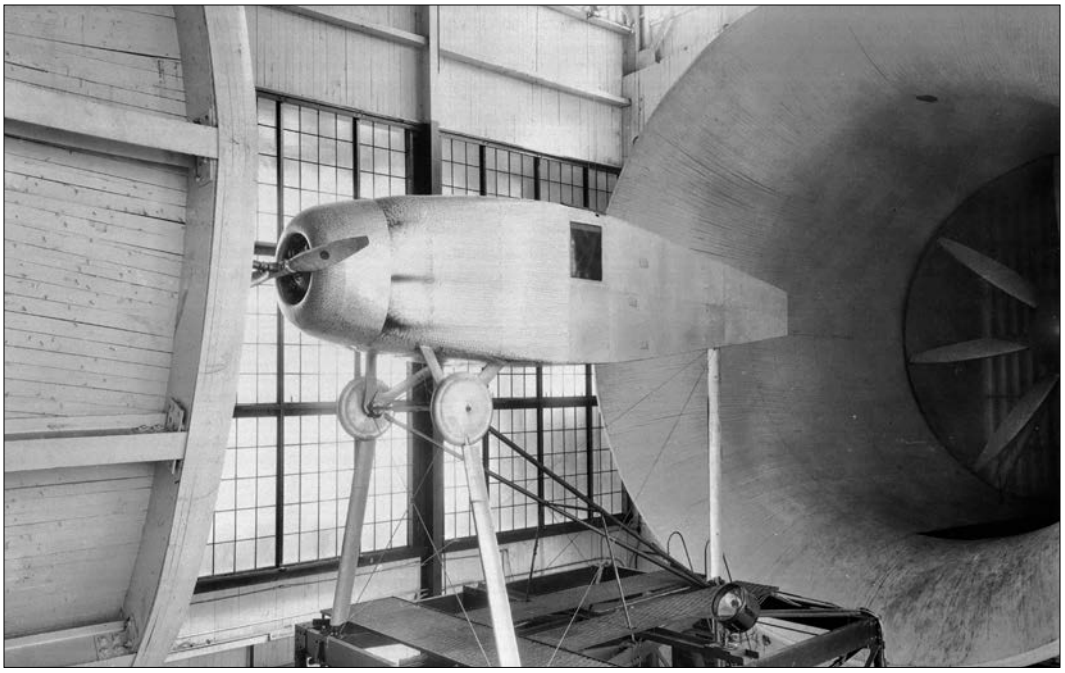
This 1930 diagram shows the simple design of the Propeller Research Tunnel's balance. Three scales (C) measured aerodynamic forces on the fuselage. Scale (T), balanced by counterweight (H), measured the propeller's thrust. (Image credit: NASA LRC-1930-B701_P-04394)



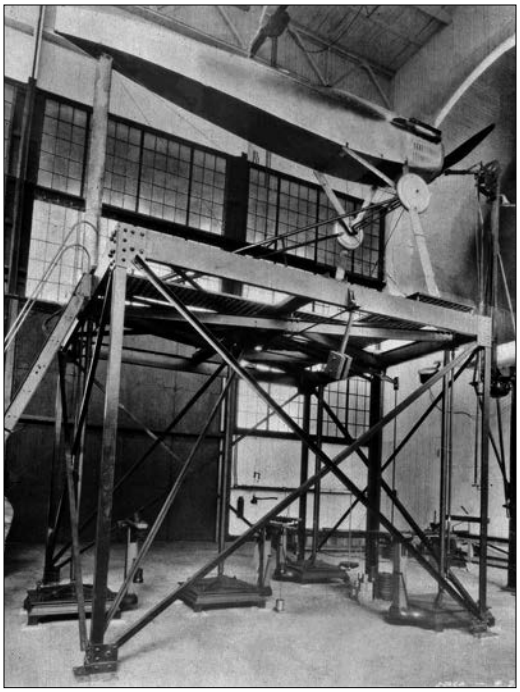
This 1928 view shows how the dynamometer, with its dial-type scale, was installed in the second cockpit of the fuselage. An operator in this cockpit controlled the engine's operation and recorded the dynamometer readings during a test. He had to climb into the cockpit on a portable ladder before the run began. One sprocket of the electric starter is visible at right. (Photo credit: NASA LRC-1928-B701_P-02305)



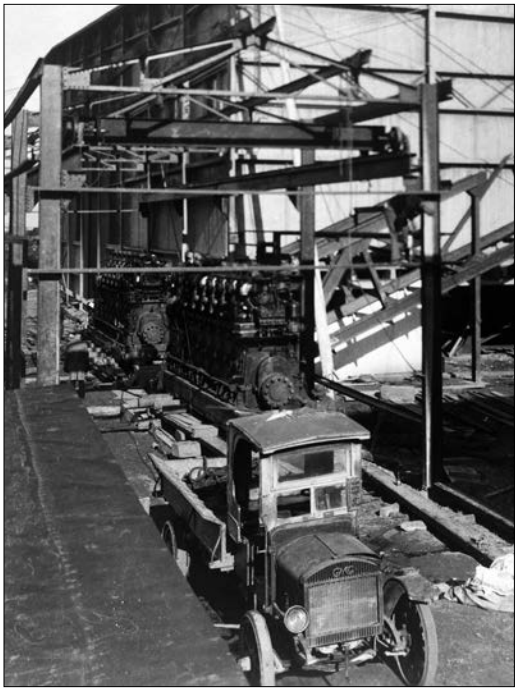
The Propeller Research Tunnel's size is clearly evident in this classic 1927 photograph of Elton W. Miller, one of the PRT's designers, standing in the tunnel's entrance cone to inspect a Sperry M-1, the first airplane tested in the new facility. Note how the plane's wings have been cropped, a practice that was soon seen as unnecessary and largely abandoned. (Photo credit: NASA LRC-1927-B701_P-01892)



This test fuselage is fitted with Cowl No. 10, the prototype for the first commercial installations. Developed in the Propeller Research Tunnel to reduce air resistance around a radial engine, the NACA Cowl proved to both lower air resistance and improve engine cooling. It earned the NACA its first Collier Trophy in 1929 and rapidly became a standard appliance for radial engines. (Photo credit: NASA LRC-1928-B701_P-02730)

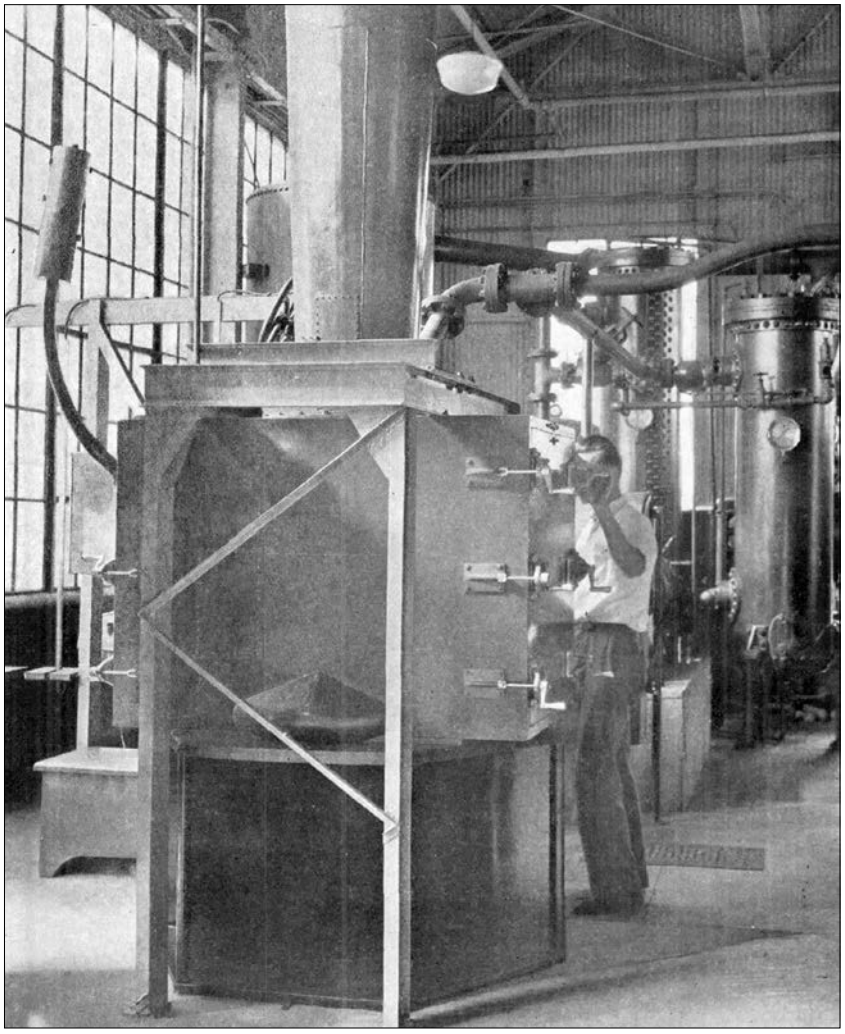


This Vought VE-7-inspired fuselage and engine, seen here in 1928, became the basic propeller-testing platform. The chain-and-sprocket arrangement at right was an electrically powered starter for the plane's engine. A dogged fitting engaged the propeller to spin it, and the device rotated out of the air stream after the engine started. Note the beam-type scales used with the balance. (Photo credit: NASA LRC-1928-B701_P-02303)



This 1920s construction photo shows the Propeller Research Tunnel's diesel engines in place. The diagonal truss structure supported the 44 drive belts needed to convey the engines' power to the tunnel's fan shaft. (Photo credit: NASA LRC-1990-B701_P-04347)

11-INCH HIGH-SPEED TUNNEL



The 11-Inch High-Speed Tunnel. Note the VDT's compressor in the background and the overhead supply pipe to the 11-Inch HST from the VDT. (Photo credit: NACA Report No. 463, Fig. 1)

SIGNIFICANCE

The 11-Inch High-Speed Tunnel (11-Inch HST) was the NACA's first wind tunnel capable of speeds close to the speed of sound (Mach 1), and it allowed researchers at Langley to begin investigations into the complex dynamic phenomena resulting from air's compressibility that begin to occur near Mach 1. The 11-Inch HST used compressed air from the VDT as its power source, making it the NACA's first case of using one test facility to support another, thus achieving substantial construction and operation economies. Tests in the 11-Inch HST demonstrated that aerodynamics changed significantly near Mach 1, thus furnishing justification for additional NACA investments in high-speed tunnels.

DESCRIPTION

The 11-Inch HST was a small, vertically oriented tunnel built next to the VDT. Completed in 1928, its outward appearance was of a wooden box approximately 4.5 feet square by 3.5 feet high, supported 2.5 feet above the floor by a simple structural steel frame. A smaller box protruded from the main box high on one side. Six radial vanes extended up from the floor to the inlet bell at the bottom of the box. A flared sheet-metal duct extended vertically from the top of the unit through the building's roof, and a short overhead pipe ran to a tee in the VDT's compressed-air supply pipe.[26]

The box, which was three layers thick, formed a sealed enclosure for the tunnel itself, and the protruding box provided space for the tunnel's photo-recording balance. Two sides were removable for access to the balance and test model.

The main portion of tunnel was inside the box. It consisted of a 7-inch-long test section 11 inches in diameter, with a flared inlet at its bottom and an annular nozzle at its top. Above the annular nozzle, a flared diffuser served as an extension of a larger nozzle with its throat being the test section. When high-pressure (starting at 300 psi) air from the VDT was injected through the annular nozzle, it induced a negative pressure in the test section. This caused a larger volume of room (atmospheric) air to be drawn into the inlet, accelerated through the test section, and out the diffuser to the atmosphere. With no model in the tunnel, the air speed through the test section would reach approximately the speed of sound, though it was substantially less with a model in place. The test-section components and the annular nozzle were of cast steel. The diffuser was 19 feet, 10 inches long, with an included angle between the walls of 4.8 degrees.

The original test section was the open throat of the nozzle, and the only major modification to the tunnel saw this changed to a closed-throat design in 1932. Though they did not change the tunnel's overall appearance, numerous minor adjustments were needed, especially during startup, to get optimum performance out of the 11-Inch HST.

Sealed inside the box, the balance, which was designed and built specifically for this application, had to function semiautomatically during each test. Models were mounted on dowels attached to a yoke that surrounded one side of the test section. This kept the support dowels outside the airstream. Researchers manually set the angle of attack before each run. A camera mounted on the balance photographically recorded force and moment data from the balance. Mirrors connected to the balance beams reflected light from a small light source onto the film, which was advanced by a small electric motor. After the throat was closed, a clever pair of penetrations in the wall used thin brass end plates to accommodate the model supports. Each pair of end plates was machined to provide 1/16-inch clearance around a particular airfoil, and they could be easily rotated to match varying angles of attack.[27]

HISTORY

As construction of the PRT neared completion in 1927, NACA engineer and head of the VDT Section Eastman Jacobs realized that the PRT would likely not answer many of

his questions. The PRT would doubtless generate good overall propeller performance data, but it would probably not contribute much to a true understanding of the high-speed—close to the speed of sound—aerodynamics near the blade tips. For this, Jacobs knew he needed a wind tunnel that could actually produce Mach 1 airflow. Only two supersonic tunnels existed at the time, a 0.8-inch blowdown tunnel at Britain's National Physical Laboratory and a temporary 2-inch, open-jet nozzle that Lyman Briggs and Hugh Dryden built at the U.S. Army's Edgewood Arsenal. Of limited practical use, they had shown that such tunnels were possible. Thinking about the large volume of compressed air exhausted to atmosphere after each test in VDT, it occurred to Jacobs that a larger blowdown tunnel powered by this air should be possible.

Jacobs designed an 11-inch tunnel with an annular nozzle set into a larger nozzle just downstream of its throat. High-pressure VDT air flowing rapidly through the annular nozzle would, according to Bernoulli's theorem, generate a partial vacuum in the larger nozzle's throat, and this would induce a larger flow of atmospheric air through the throat, where a test model could be placed. With the right proportions and airflow through the annular nozzle, Jacobs's calculations indicated that the induced flow could reach the speed of sound in the throat. Trading off throat diameter and air consumption, Jacobs ended up deciding to use an 11-inch-diameter throat. With that size, the VDT contained enough air for Mach 1 test runs of about a minute, but that would be long enough to generate useful data. Since a propeller blade was an airfoil, simple airfoil models would be his models. Each could be tested at various speeds and angles of attack to suit its position along the blade.[28]

Jacobs's design featured a vertical-flow tunnel with an open test section inside a sealed enclosure. Air would be sucked from near the floor and exhausted above the building's roof. The exhaust stack was actually the diffuser portion of the nozzle. Flared at an included angle of 4.8 degrees, its 19-foot, 10-inch length substantially increased the nozzle's performance and efficiency. The tunnel's inlet was approximately 2.5 feet above the floor. It featured an elliptical inlet bell and six radial vanes to eliminate swirl as the air turned into the inlet. The nozzle throat and the annular nozzle ring were cast of steel and machined to their precise contours. The test section, which would be under vacuum, was enclosed within a three-layer wooden box with two removable sides to provide balance and model access.

A unique balance was required. It had to fit inside the enclosure, support the model at previously unknown speeds without disturbing the airflow, and still accurately record a wide range of force and moment data. Additionally, it had to do so quickly and without direct operator attention during tests that would be very short. The resulting balance supported both ends of the airfoil models on a yoked arm that remained outside the airstream. The yoke was adjustable to various angles of attack. This strongly influenced the open-throat design as it allowed the airfoils to extend beyond the airstream and avoid support disturbances. The yoke transmitted forces to three cantilevered steel spring beams. Each beam was linked to a pivoted mirror, which reflected a small beam

of light onto photographic film. These traces on the film yielded the aerodynamic forces and moments. The camera included a three-speed drive to advance the film as the test progressed, set in advance by the operator to suit the test speed.

Since no new power supply was necessary, the 11-Inch High-Speed Tunnel was inexpensive to build, costing only about $10,000, and it entered service in 1928. Operations had to be closely coordinated with the VDT, but with Jacobs as the section head, that posed few problems.

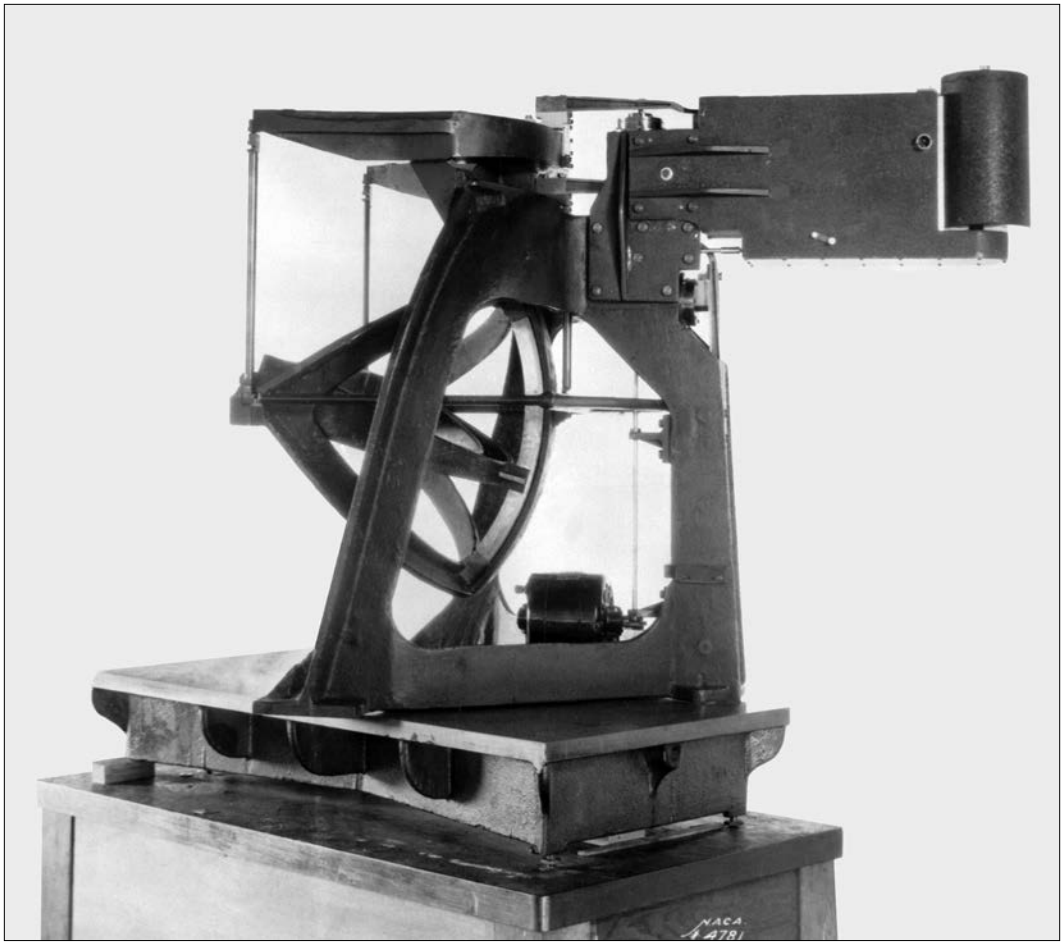
A typical test used a machined steel airfoil with a 2-inch chord. Once it was mounted on the balance yoke, the angle of attack and camera speed were set, and the enclosure clamped shut. Opening a valve in the VDT's air pipe started the airflow, and the camera was started as soon as stable conditions were observed on a mercury manometer. Throttling the high-pressure flow with the supply valve lowered the test speed in increments until the desired speed range had been covered. Researchers then opened the box, set a new angle of attack on the balance, and repeated the procedure. While the number of tests that could be run before the air pressure fell to a useless value varied with the speed range, careful management and automatic data recording on film usually allowed an airfoil to be tested over the full speed range at two angles of attack. By throttling the airflow in stages, the two test series typically involved about 24 minutes of actual running. After the test runs, the film was developed and the beam deflections on it carefully measured. Using calibration charts, the corresponding forces and moments were easily determined, and the standard airfoil coefficients calculated.[29]

Like other aerodynamicists, Jacobs well knew that air was a compressible gas, but no one really knew what the effect of that would be at speeds far greater than any airplane could then fly. At slow speeds, compressibility could be neglected, but the tests with propeller airfoils indicated that detrimental effects increased above about Mach 0.8. Lift, or thrust, began to decrease, the center of pressure on the airfoil moved further aft, and drag rose dramatically. The 11-Inch HST measured these effects, but more investigation was needed to even to begin to understand why they occurred.

About the time the 11-Inch HST opened, Jacobs added a recent graduate, John Stack, to his staff, and Stack quickly developed an intense curiosity about high-speed aerodynamics. Seeking to improve the stability of the tunnel's airflow, Stack and Walter F. Lindsey, another recent graduate engineer, designed a closed-throat test section for it. The biggest challenge was finding a way to support the model through a closed wall without touching that wall. They designed a pair of penetrations in the wall that used thin brass end plates mounted in circular openings. Each pair of end plates was machined to provide 1/16-inch clearance around a particular airfoil, and they could be easily rotated to match varying angles of attack. The small gap permitted the airfoil movement needed without disturbing the airflow. This modification, the only major one to the 11-Inch HST, proved successful, and the tunnel operated in this configuration for the rest of its life.

While most operation was routine, one incident involving this tunnel stands out. Amelia Earhart toured Langley in November 1928, and because of the weather wore a long fur coat much of the time. She must have gotten a bit too close to the 11-Inch HST during a demonstration, because the intake airflow sucked part of her coat in toward the inlet. Earhart was unharmed, though no doubt a bit rattled, and no record survives of any damage to her coat.

The 11-Inch HST was ultimately demolished, probably before 1940, but the precise date is uncertain. No portion of it remains. Even as it was being modified with a closed throat in 1933, construction of its successor, the 24-Inch High-Speed Tunnel, was under way. Except for being more than twice as large, the new tunnel was very similar to the pioneering 11-Inch HST.



The original balance for the 11-Inch High-Speed Tunnel, seen here in 1930. Airfoil models were attached to the triangular mount and scale on the left, and a camera (not shown) recorded the data. (Photo credit: NASA LRC-1930-B701_P-04781)

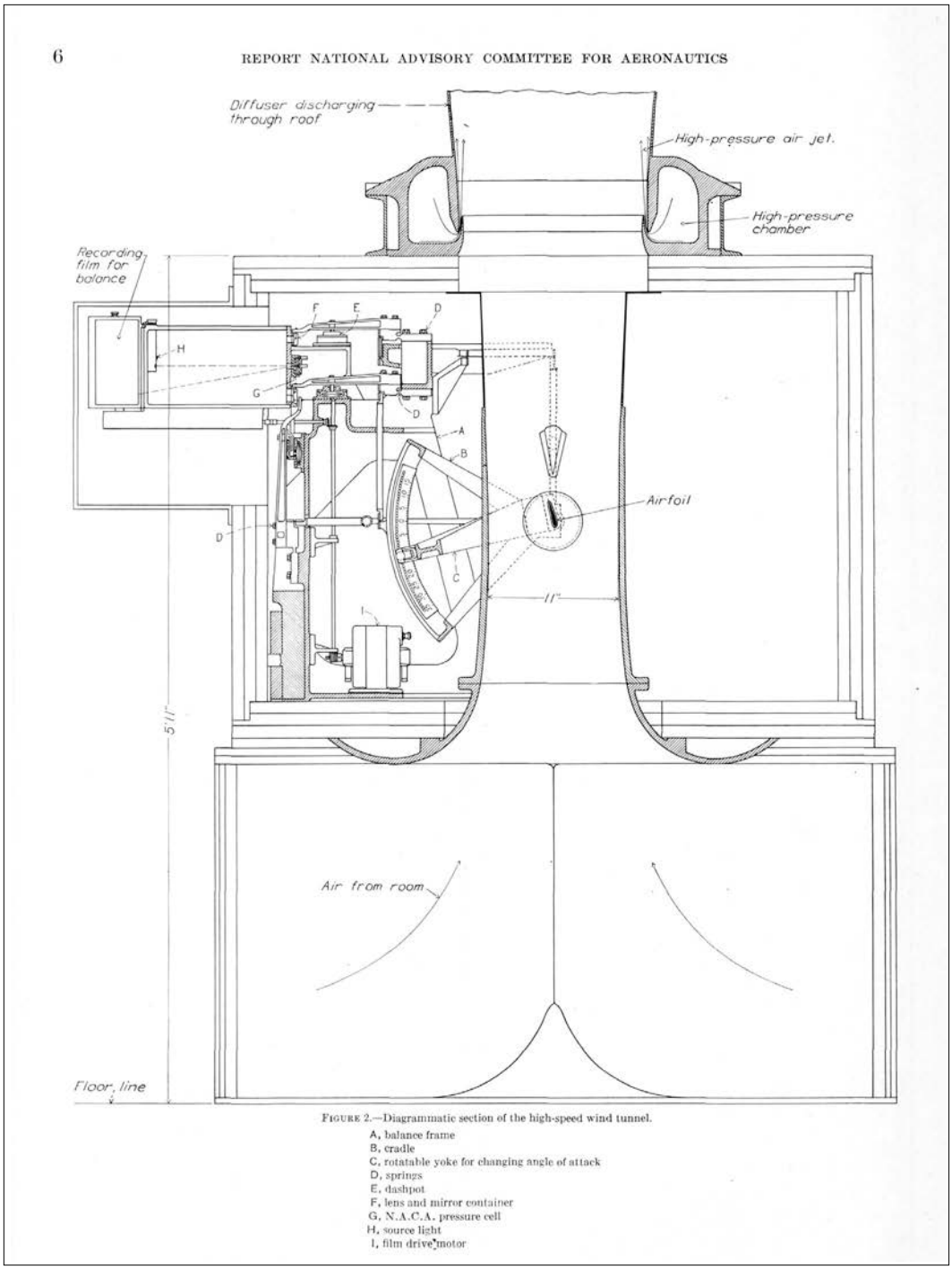
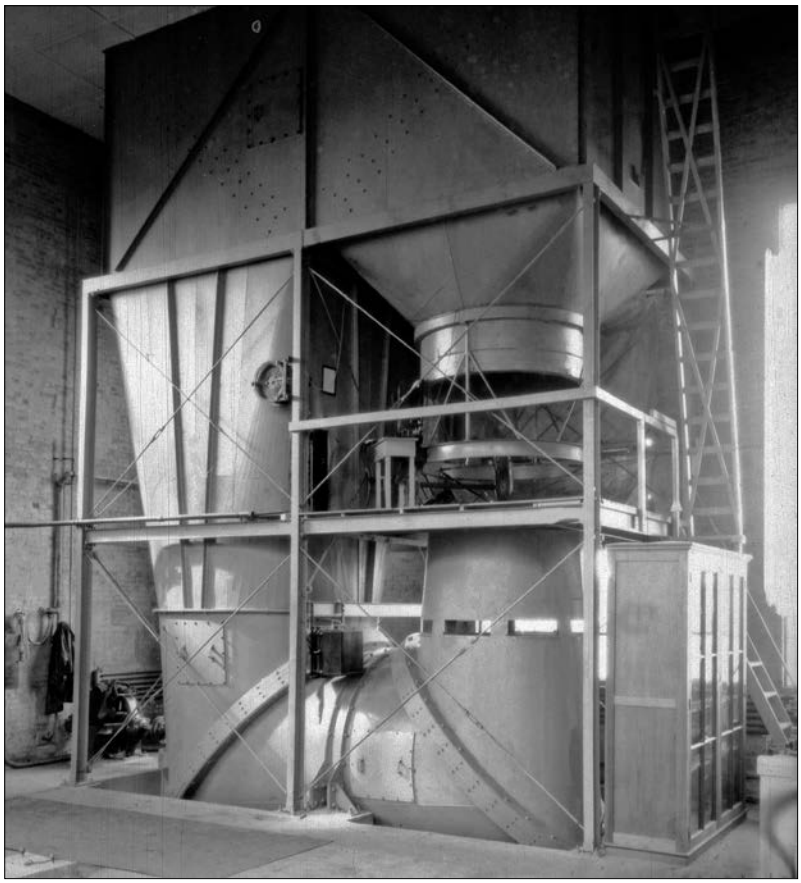


FIGURE 2.—Diagrammatic section of the high-speed wind tunnel.

A, balance frame
B, cradle
C, rotatable yoke for changing angle of attack
D, springs
E, dashpot
F, lens and mirror container
G, N.A.C.A. pressure cell
H, source light
I, film drive motor

This drawing shows the 11-Inch High-Speed Tunnel as modified with a closed throat. The biggest modification challenge was designing a seal for the airfoil-balance mount. The long diffuser above the annular nozzle is not shown in either drawing. (Image credit: NACA Report No. 463, Fig. 2)

5-FOOT VERTICAL WIND TUNNEL
4- BY 6-FOOT VERTICAL TUNNEL



This 1930 view shows the 5-Foot Vertical Wind Tunnel shortly after its installation in Building 60 (now Building 190). Note the elevated platform around the open test section. (Photo credit: NASA LRC-1930-B701_P-04392)

SIGNIFICANCE

The 5-Foot Vertical Wind Tunnel (VWT) was the NACA's first wind tunnel built specifically to study the spinning characteristics of airplanes. This also made the VWT the committee's first tunnel to investigate the actions and effects of control surfaces, especially in undesirable situations. The VWT became the first of a series of tunnels built at Langley and elsewhere whose primary research area was flight safety rather than aircraft performance and efficiency. The VWT was later modified with a closed test section and renamed the 4- by 6-Foot Vertical Tunnel.

DESCRIPTION

The VWT was a self-contained machine constructed of sheet steel and supported by an external structural-steel frame. It rested on a concrete perimeter foundation that

surrounded a 3-foot-deep pit in the floor of the building originally built for Wind Tunnel Number 1, which was demolished prior to the VWT's construction. In plan, the VWT measured 20 feet, 3 inches by 10 feet, 3 inches, and it stood 28 feet, 2.625 inches above the floor. Its 50-horsepower, DC motor extended just over 6 feet from one end at floor level.[30]

The VWT was specifically designed to have downward vertical airflow through an open test section, giving the entire tunnel a vertical orientation. Otherwise, it had the standard characteristics of other closed-circuit wind tunnels, including turning vanes in its corners, a propeller downstream from the test section, an enlarging return passage, and a settling chamber just ahead of the test section nozzle. The test section and lower portion of the tunnel had a circular cross section that transitioned to square in the upper section, with the settling chamber being 9 feet square. The contraction nozzle (entrance cone) transitioned back to a 5-foot-diameter circle. The test section measured 3 feet, 11 inches in length. It was surrounded by a platform 10 feet above the floor. The exit cone opening was flush with this platform. It was not flared, but an annular gap around it furnished a path for spillage air.

The VWT was modified to enclose the test section in 1938, and it retained that configuration until its deactivation. The modification changed the test section to a 4- by 6-foot rectangular cross section, which allowed models with a 1-foot greater wingspan than the original design.

HISTORY

Not all of the problems the NACA wanted to tackle involved airplane design for speed and efficiency. Safety in flight was equally important, especially if commercial air service was to grow and prosper. Thus, in 1928 the NACA decided to replace its obsolete Tunnel Number 1 with two new wind tunnels designed to address safety problems. One was a conventional, horizontal tunnel, but the second had a vertical airflow. The two tunnels were viewed as complementary, and the same team worked on both. The tunnels were designed to both fit in the building vacated by Tunnel No. 1.

One of the most vexing safety problems involved spins, which often resulted when an airplane was inadvertently flown beyond a critical angle of attack during maneuvers, stalled, and autorotated in a corkscrew path toward the ground. In many instances, a pilot's attempts to recover from a spin actually aggravated the situation. Crashes were all too common, but why spins occurred and how to recover from them were poorly understood. Engineers at Langley wanted to know the roles played by both airplane design and piloting, and if any specific maneuvers might help a pilot regain control from a spin. Charles H. Zimmerman, a young engineer at Langley, had an intense interest in flight control, and he suggested that a wind tunnel be built specifically to investigate spin behavior.

Zimmerman's proposal was approved in 1928, and he began finalizing the design immediately. He wanted to support a model at its center of mass on a rotating balance with an arm to hold the model at the desired spin radius. In a horizontal tunnel, the

gravitational force acting on a model and balance rotating about a horizontal axis would alternate in direction and never match the direction an actual airplane would experience during a spin. Since an airplane in a classic spin rotated or circled around a vertical axis under a constant gravitational force as it descended, selecting a vertical design for the tunnel solved this problem. Zimmerman employed a downward airflow that acted on an inverted model. He used a variable-speed electric motor with a control at the test section to control the airspeed up to 80 mph. A second, smaller motor turned the balance.[31]

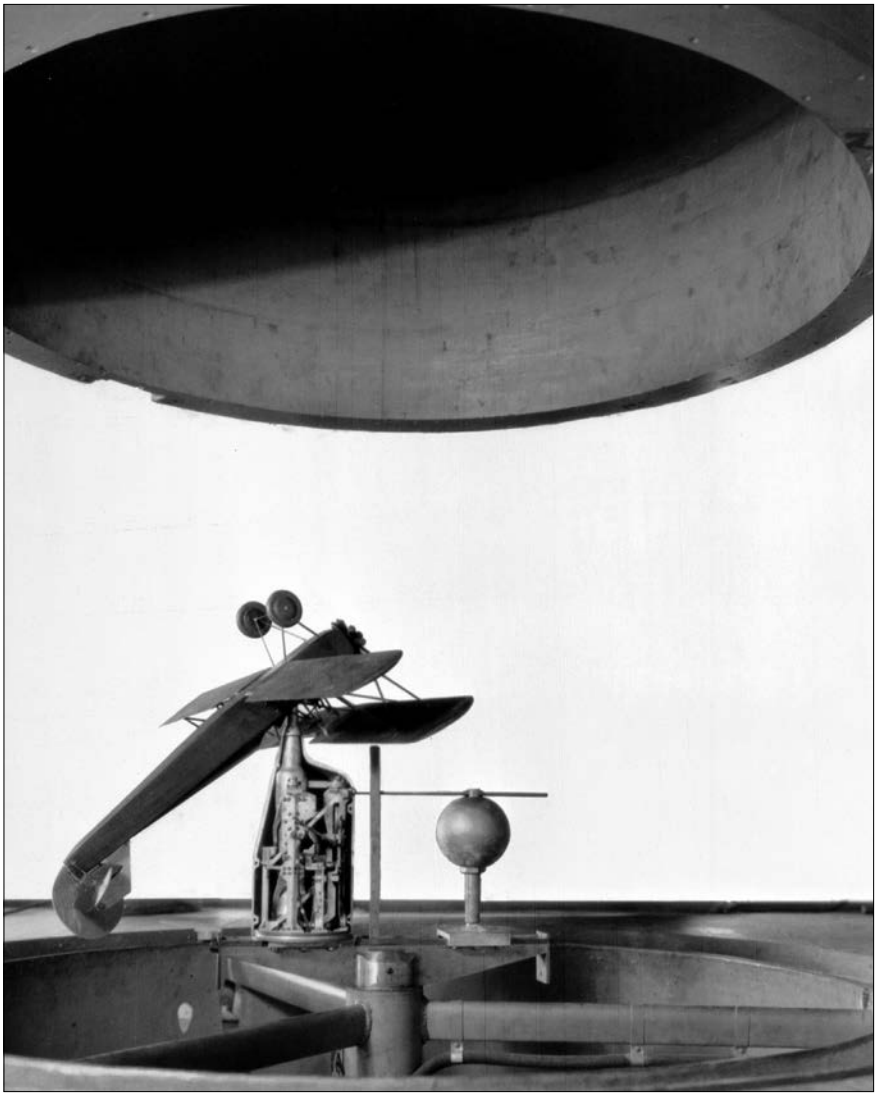
The tunnel was completed in December 1929, but a useful balance took longer to perfect. The spinning balance was a daunting design challenge because the model was not fixed in one position within the tunnel. To study spins, the entire model had to move in a circular pattern, and the balance had to accurately record force and moment data while following this movement without resisting it. A successful design finally went into service about three years after the tunnel opened. It mounted the model inverted on a vertical spindle, with a lockable pivot at the connection to allow varying angles of attack to be set. The spindle had six degrees of freedom and was linked to six measuring units. This entire balance assembly was mounted on a turntable arm that rotated about the tunnel's centerline. The balance could be mounted on the arm at any radius of spin between 0 and 8 inches. The balance spindle and turntable arm rotated in self-aligning ball bearings to minimize friction. A pneumatic measuring system used adjustable air pressure to balance forces on the six load beams, with the required air pressure indicating the opposing force. With only one oil-sealed rotating joint on the turntable shaft, readings had to be taken one at a time, but time presented no problem in the constant-flow tunnel.[32]

Once a reliable balance and test routine had been established, Zimmerman and his team, which included Carl Wenzinger and Thomas Harris, began to identify key characteristics of stall-friendly and stall-averse airplanes, as well as some good and bad pilot responses. These studies began to suggest stall-recovery techniques that were ultimately evaluated further in Langley's 15-Foot Spin Tunnel (15-Foot ST), which allowed models to spin free, and then tested in flight.

Within a decade, two factors prompted new uses for the VWT. The 15-Foot ST opened in 1935, and while spin-recovery research continued, attention began to focus more heavily on the design and performance of aircraft control surfaces in all flight conditions. Control forces had increased to problem levels as planes got larger and faster, so the NACA modified the VWT in 1938 to support investigations aimed at optimizing control-surface performance. While the vertical flow direction made no difference to these tests, the VWT was otherwise reasonably suited for them. To accommodate larger models (in a fixed position instead of spinning), the test section was converted to a closed 4- by 6-foot configuration. The instrumentation also changed, with a fixed balance replacing the spinning balance and the addition of multiple manometers for pressure-distribution studies around control surfaces. The tunnel's top speed dropped

to 65 mph, proportional to the 23 percent test section area increase. The tunnel's name was changed to reflect its new size at this time.[33]

As with some other early NACA tunnels, records of the date of deactivation and demolition of the VWT seem to have been lost, but it was probably dismantled shortly after World War II so the building could be converted into an office building. Although subsequently upgraded and modernized at least once more, the building continues in that service.



Model of a U.S. Navy NY-1 mounted on the Vertical Wind Tunnel's spinning balance in 1932. The airflow is downward. (Photo credit: NASA LRC-1932-B701_P-07023)

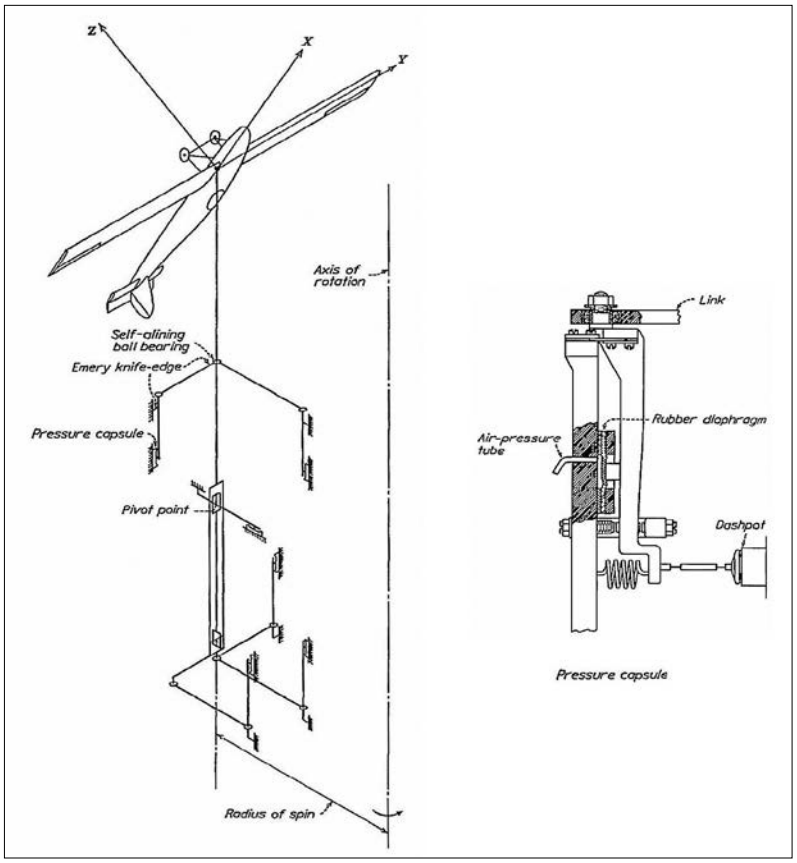
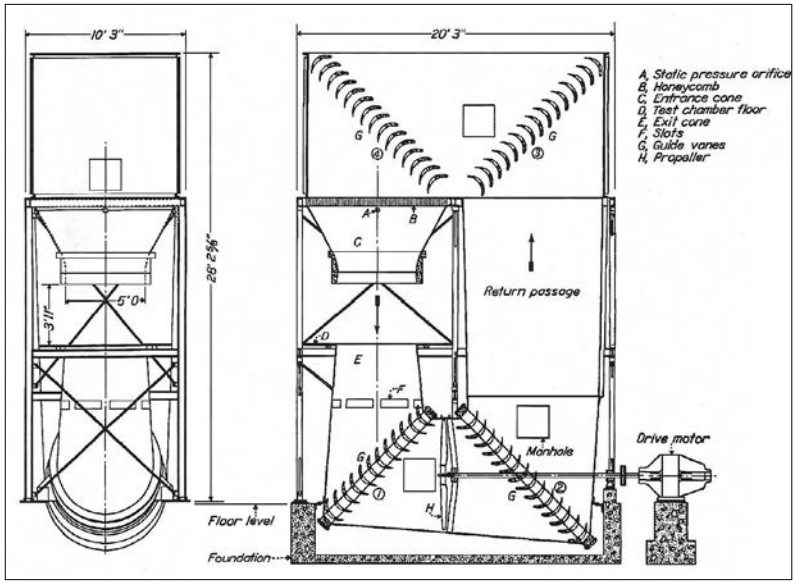


Diagram of the Vertical Wind Tunnel's spinning balance, with a detail of one of six pressure capsules. Air pressure against the rubber diaphragm balanced aerodynamic force through the link. (Image credit: NACA Report No. 607, Fig. 1)



This drawing of the 5-Foot Vertical Wind Tunnel shows its vertical arrangement with a downward flow through the test section. Its major components are identified. (Image credit: NACA Report No. 387, Fig. 1)

7- BY 10-FOOT ATMOSPHERIC WIND TUNNEL

Looking downstream through the entrance cone into the 7- by 10-Foot Atmospheric Wind Tunnel's open test section in 1931. Note the six-bladed propeller in the background and the control panel at left. (Photo credit: LRC-1931-B701_P-05812)

SIGNIFICANCE

Opened in 1930, the 7- by 10-Foot Atmospheric Wind Tunnel (7 × 10 AWT) was the first of several wind tunnels of this size built by the NACA and others. While this tunnel was not outstanding in any performance specification, its 7- by 10-foot size and proportion proved to be well suited to monoplane designs. The 7 × 10 AWT became a workhorse capable of performing a wide variety of low-speed tests at relatively low cost.

DESCRIPTION

Like the 5-Foot Vertical Wind Tunnel (5-Foot VWT), the 7 × 10 AWT was erected in the original Langley wind tunnel building (Building 60, later renumbered 190) after Tunnel Number 1 was dismantled. Though having a horizontal orientation, its construction, using ⅛-inch steel sheet and structural members, also bore similarities to the vertical tunnel, which is not surprising since they were built at the same time, with Carl Wenzinger and Thomas Harris responsible for both designs.

The 7 × 10 AWT measured 63 feet, 2.125 inches long, not including its drive motor, and it stood 27 feet, 5 inches above the floor. It was 20 feet in diameter at its largest point. Because of the relatively narrow building, the 7 × 10 AWT was designed with its return leg above its test leg rather than beside it. As built, the tunnel had an open test section,

though it was enclosed in 1938. The closed test section featured rounded corners between the walls and ceiling and floor. All four corners of the circuit had turning vanes, and a honeycomb flow straightener was mounted just ahead of the entrance cone. During calibration tests, the designers installed wire screens over portions of the honeycomb to further improve the flow uniformity.[34]

HISTORY

In 1928, the NACA decided to replace its obsolete Tunnel Number 1 with two new wind tunnels. Engineers at Langley wanted to know the roles played by both piloting and airplane design, particularly if any design features would improve or worsen an airplane's stability and controllability. One of these tunnels was a vertical one for investigating spins, and the second was a more-conventional, horizontal-flow tunnel, the 7 × 10 AWT. It would be useful for a variety of aerodynamic tests, but like its vertical companion, the initial emphasis was on flight safety, specifically stability and control. The two tunnels were planned to be complementary, and the same design team worked with Charles H. Zimmerman on both. The tunnels were designed so that both would fit in the building vacated by Tunnel Number 1.

The tunnel's general arrangement was a bit unusual in that its return leg was installed above the test section and fan, rather than beside it. The dimensions of the existing building necessitated this, but it made no difference in the tunnel's performance. The available room did affect the tunnel's size to some degree, but the 7-foot by 10-foot size primarily resulted from an intelligent design consideration. By 1928, it was starting to become clear that monoplanes with internally braced wings would largely replace biplanes before long, and monoplanes would have wider wingspans. Thus, wind tunnels needed to grow wider in proportion to their height, and this proportion yielded a comfortable airflow around all portions of a monoplane model, whether it was of an airfoil or a complete airplane.

With the size decided, Zimmerman, along with Thomas Harris and Carl Wenzinger, completed their calculations and drawings for the remainder of the tunnel, using the same basic type of construction and many of the same details they employed in the 5-Foot Vertical Tunnel. Both were fabricated from sheet steel and supported by an external, structural steel frame.

The tunnel used a 6-blade propeller, 10 feet, 6 inches in diameter, that was driven by a 200-horsepower DC motor. The combination delivered a top speed of 80 mph, and it introduced two new features at Langley. The pitch of the propeller blades could be adjusted before a run to obtain the best performance, but use of this feature does not appear in test reports, so it appears that an optimum setting was determined during the tunnel's initial calibration runs and seldom, if ever, changed after that. The second innovation proved more useful. It was a dynamic pressure control device that automatically made fine speed adjustments to the motor to maintain the dynamic pressure of the air against the model constant within ± 0.2 percent. Its feedback signal was the test

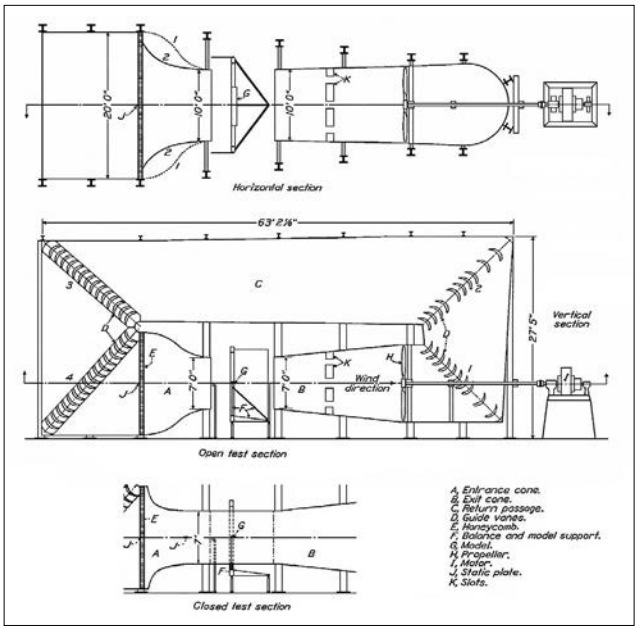
section's static pressure, which acted upon a manometric balance. The balance's beam was connected to an electrical circuit that controlled the motor by making minute changes in the resistance of the motor's field coils.

Since this tunnel was primarily intended for stability testing, its balance was designed to accommodate both static and rotational tests. Like other six-component balances of the era, this one used mechanical linkages and multiple mechanical scales, but its frame could accommodate an alternate model support with a rotating horizontal spindle. A small motor drove this spindle when specific rotational rates were desired, or it was allowed to rotate freely for autorotation tests.[35]

The 7 × 10 AWT entered service in July 1930, and it soon became a workhorse for low-speed testing, including long, systematic test programs to study stability, control, and high-lift devices. These programs usually used wings rather than complete airplanes, with typical wing models having approximately 10-inch chords and 60-inch spans.

During the 1930s, larger, faster airplanes increasingly challenged designers to devise wings that had minimal drag at cruising speed, but with enough low-speed lift to enable safe landings and takeoffs. The most effective way to accomplish both was to add movable flaps and/or slats to increase the wing's camber, thus lift, at low speeds, but the unknown effectiveness of the many possibilities caused Wenzinger and Thomas to initiate a series of tests involving various high-lift devices. About 1938, Wenzinger's team decided to enclose the test sections of the 5-Foot VWT and the 7 × 10 AWT, believing they would obtain smoother airflow. Accordingly, the 7 × 10 AWT received a fully enclosed test section with the same dimensions as before, along with a new entrance cone that had a sharper contraction, and its balance received minor modifications to clear the new walls. The turbulence actually increased slightly, but the arrangement permitted two-dimensional testing of models with larger chords that completely spanned the width of the tunnel. Such models were ideal for tests involving high-lift devices like flaps, slats, and slots, and the tunnel saw considerable use in this service through World War II.[36]

Once the test section had been enclosed, technicians realized another benefit to the 7- by 10-foot size; they could stand upright in it while installing or adjusting models, a matter of no small convenience. With proportions well suited to modern monoplanes and a very practical size, from both setup and operating perspectives, the 7 × 10 AWT became the prototype for four additional NACA wind tunnels, two at Langley and two at Ames, that entered service about the war's end. These newer tunnels had capabilities that far exceeded those of the 7- by 10-Foot AWT, and it fell into disuse after the war, being deactivated about 1946 and dismantled sometime later.



Drawings of the 7- by 10-Foot Atmospheric Wind Tunnel. The upper drawings show it as built with an open test section, and the small drawing at the bottom shows the modification that reshaped the entrance cone and enclosed the test section in 1938. The original balance was retained but modified slightly to suit the new arrangement. (Image credit: NACA Report No. 412, Fig. 1)

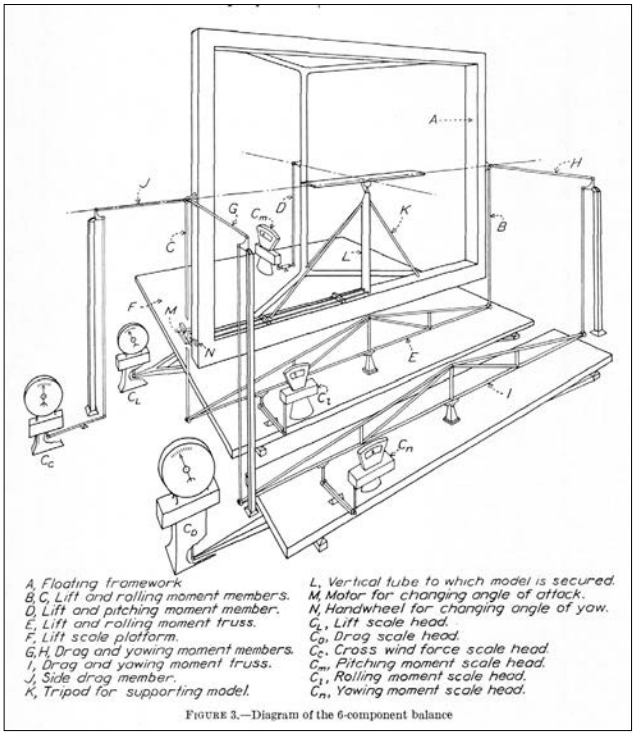
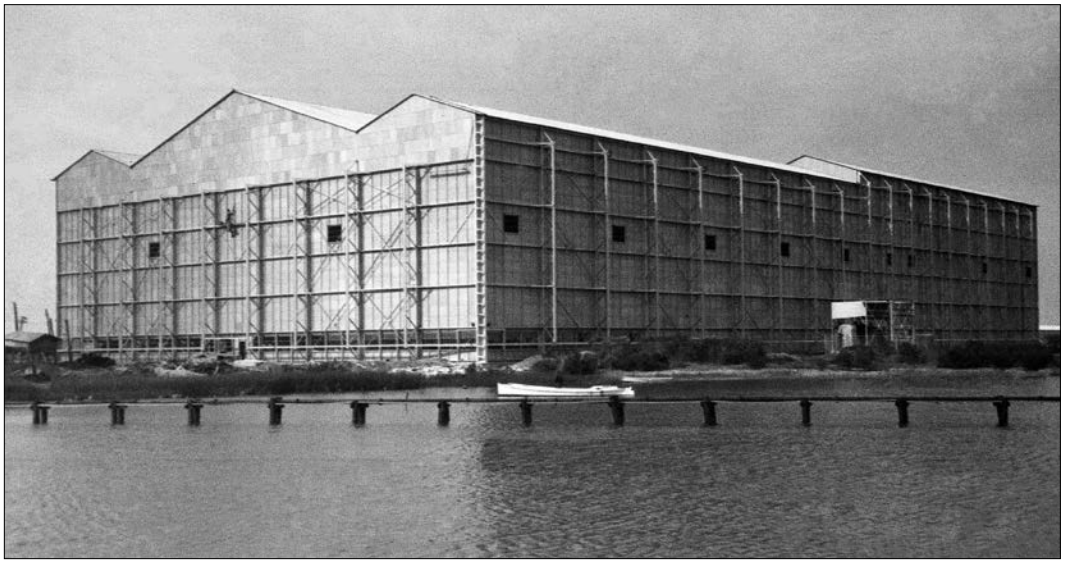


Diagram of the 7- by 10-Foot Atmospheric Wind Tunnel's six-component balance with its major parts labeled. Its measurements would yield the three forces and three moments needed to define the model's aerodynamic performance. (Image credit: NACA Report No. 412, Fig. 3)

FULL-SCALE TUNNEL



The Full-Scale Tunnel, seen from across the Back River shortly after its completion in 1931. With no common items discernable in this photo, it is difficult to appreciate the tunnel's enormous size. (Photo credit: NASA LRC-1930-B701_P-04933)

SIGNIFICANCE

The Full-Scale Tunnel (FST) was the world's first wind tunnel large enough to accommodate a full-sized airplane for aerodynamic testing, thus providing a direct comparison and correlation between actual flight and wind tunnel testing. As such, it complemented the small model testing done under pressure in the Variable-Density Tunnel (VDT) and allowed each tunnel to validate the other's results. Additionally, the FST provided in-flight Reynolds numbers at a low turbulence level the VDT could not match. Equipped with an advanced six-component balance and airflow survey equipment, the FST significantly advanced the technology of wind tunnel testing, and new equipment added during its life kept it a useful facility well into the Space Age. It was designated a National Historic Landmark in 1985 and is currently NASA's oldest serviceable wind tunnel.

DESCRIPTION

Like the Propeller Research Tunnel (PRT), the FST is an integrated design with dual return ducts whose outer walls form the building walls. It is, however, about 2.5 times larger, measuring 434 feet, 6 inches by 222 feet and having a maximum height of 97 feet. The roof, exterior walls, and many of the interior walls are sheathed in a then-new material called "Careystone," an asbestos-cement material formed into panels and pipe that was both fire- and weather-resistant. All of the FST's exterior panels are corrugated Careystone. An external, structural steel frame supports the wall panels, and internal steel trusses brace the roof. A single-story office and shop structure was added to the

southwest end sometime after 1930. Other office, shop, electrical equipment, and storage spaces occupy areas beneath the tunnel.[37]

The test chamber is located in the middle of the structure. Its elliptical nozzle, built of wood, delivers an airstream that measures 30 by 60 feet and attains velocities of up to 118 mph through the 56-foot-long open-jet test section. A bell-mouthed exit cone collects this air and directs it to a streamlined splitter that divides the flow for the two propellers located just downstream. This splitter also transitions the duct from a 31-foot, 6-inch by 63-foot ellipse into two 35-foot, 6.5-inch circular ducts at the propellers. As in the PRT, the test chamber is enclosed to make the FST an Eiffel-type tunnel, and large doors on its northwest side furnish access through one of the return ducts.

Each of the two 35-foot, 5-inch-diameter propellers is mounted on a streamlined nacelle that houses a 4,000-horsepower electric motor. Beyond each propeller, a return duct transitions to a 46-foot-square section at the first turn. The return legs remain rectangular in section through to the settling chamber, where the two flows recombine just ahead of the entrance cone, and their size gradually increases to 72 feet by 52 feet, 6 inches at the entrance to the settling chamber. All eight corners have turning vanes. The gradual enlargement of the return legs reduces the speed of the air, reducing wall friction and airflow turbulence.

The test chamber initially included both a six-component balance and overhead survey equipment to measure airflows around the test subject. Other instrumentation was added over the years to suit particular test programs.

HISTORY

By 1930, the VDT had proven that wind tunnel testing of models at high Reynolds numbers produced reliable data that accurately predicted the performance of airfoils, and the PRT had shown the value of full-scale testing in determining the drag characteristics of components plus the synergistic effects of fully integrating the various components into an airplane. Still, neither tunnel totally reproduced the conditions experienced by a complete airplane in flight, so the NACA decided to take an unprecedented leap and build a wind tunnel capable of testing full-sized aircraft. The FST, completed in 1931, was gigantic in all respects, and it loomed over every other structure at the Langley laboratory and airfield.

Design of the FST began in 1929, led by Smith J. "Smitty" DeFrance, who would head the FST group. The team soon settled on a 30- by 60-foot, open-jet test section with dual return legs. While this layout was similar to that of the PRT, the elliptical nozzle and exit cone needed were untried elements, as was the concept of utilizing a separate propeller in each return circuit. To find any possible problems with their design, DeFrance and his team built a 1/15-scale (2- by 4-foot test section) model. It worked very well, validating their design. (This pilot model was used from time to time for small-scale testing after the FST's completion, and it survives in an enclosed room added to the southwest side of the FST known as the Hangar.) Construction of the FST began in spring 1930, and

it ran for the first time a year later. The FST's official dedication occurred during the NACA's Sixth Annual Aircraft Engineering Conference on 27 May 1931.[38]

Two 35-foot, 5-inch-diameter propellers, each driven by a 4,000-horsepower electric motor, circulated almost 160 tons of air through the 838-foot-long dual circuit. The two motors were induction-type, alternating-current (AC) motors instead of the DC ones more commonly used in smaller wind tunnels. The AC drive saved almost 30 percent on the initial cost over a comparable DC drive. The AC motors had 24-step speed control between 75 and 300 revolutions per minute, but the discrete steps could be trimmed by varying the resistance in the armature coils to produce stable air speeds between 25 and 118 mph. Each motor was mounted in a streamlined nacelle to offer the minimum resistance to the airflow. The control switchgear and resistor banks were located directly below the fan-and-motor portion of the tunnel, with the control console in the test chamber.[39]

The FST was equipped with the most modern, six-component balance yet built to measure forces in three directions and moments about all three axes of rotation. While similar in concept to other six-component balances, it was considerably larger and heavier. It used seven Toledo scales to measure the various forces, and each scale was equipped with a remotely actuated printer that allowed an operator to simultaneously print all seven readings on paper tapes at the touch of a single button. In an era before tricycle landing gears, the balance supported test planes by their two main landing struts and tail skid. The tail strut included a lag screw to enable changes in angle of attack. Though replaced by electronic instrumentation during the 1960s, all of the balance mechanism below the test-section floor remains intact.[40]

In addition to the balance, the FST featured elaborate equipment to measure local airflows around the airplane during tests. Tubes to detect pitot, pitch, and yaw flows were mounted on a probe that was itself suspended from a movable, overhead bridge known as the survey apparatus that could position the probe almost anywhere within the test section and at any angle. This equipment proved especially useful in studying the complex flow around tail planes and the downwash behind wings.[41]

The FST could handle airplanes or large-scale models with wingspans of up to 45 feet. While the FST's speeds were not extraordinary, they were sufficient to enable measurements that could be confidently extrapolated to cover the aircraft's entire speed range because no scale factor was needed. One of the FST's better-known roles was "drag cleanup," a program begun in 1938 with the Brewster XF2A-1 Buffalo and continued through World War II. The FST team evaluated virtually every aspect of surface irregularity, such as air scoops, antennas, fairings, and even rivets to minimize the drag of almost every pre-jet American fighter airplane.

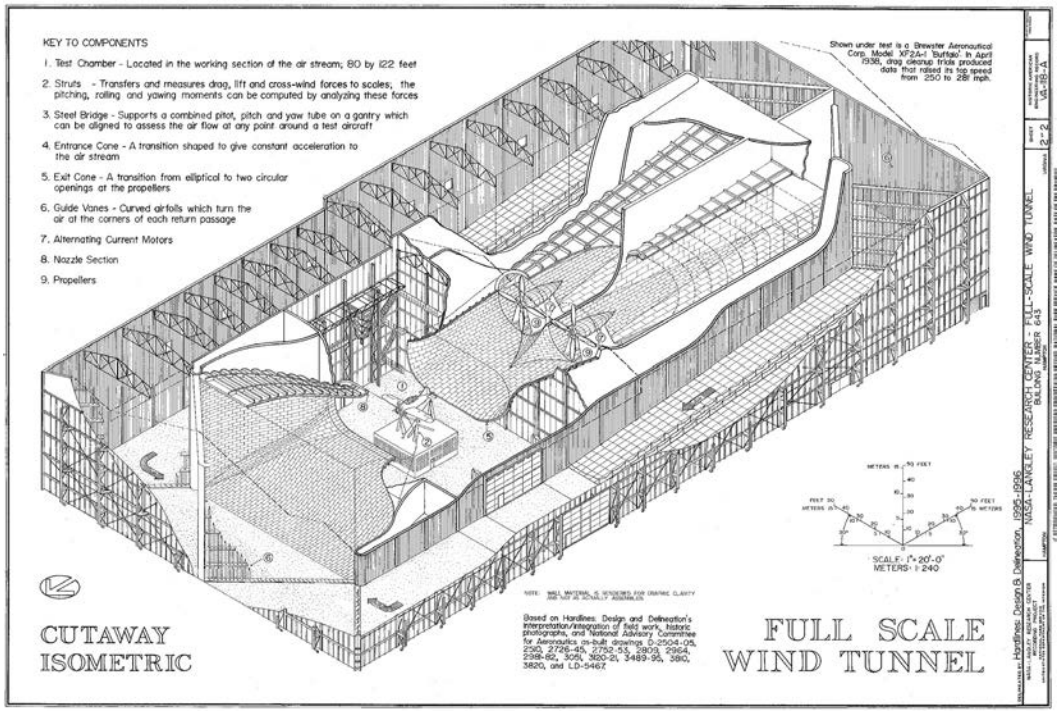
NACA and NASA researchers ultimately found that the FST could be used for a wide variety of investigations that its designers could never have imagined, and they added equipment to improve capabilities and measurement accuracy over the years. When the U.S. Navy began evaluating advanced designs for submarines, no water tunnel could

accommodate the model needed, so a model of what became the U.S.S. Albacore, the first submarine with a teardrop shape, went into the FST during 1950. Later that decade, full-scale models of the Mercury spacecraft were tested as well. In the 1960s, the FST acquired equipment to permit actively controlled models to fly free in its airstream. These large-scale models used compressed air for thrust, and three pilots cooperatively flew them, one seated in a "cockpit" located just below the exit cone and two others in a balcony room overlooking the test section. The survey apparatus held a festoon supporting the control/power umbilical to the model. This capability proved useful in the evaluation of low-speed handling characteristics of high-performance airplanes, including the F-111 and several proposed designs for an American supersonic transport.[42]

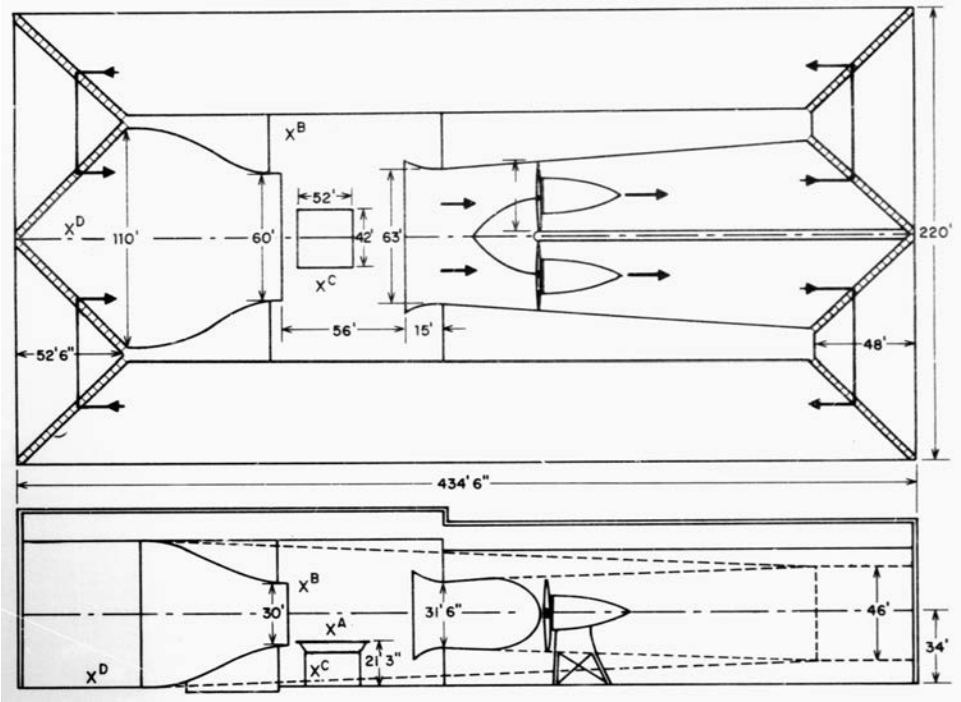
The Full-Scale Tunnel was NASA's oldest surviving wind tunnel before its last test was conducted on 4 September 2009. The tunnel had been one of the agency's most significant in terms of aviation history. The tunnel not only hosted a wide variety of tests, particularly during the "design revolution" period of the 1930s, but it served as the prototype for other full-scale tunnels in the United States and abroad, and it demonstrated how older facilities can be modernized economically to meet new needs. This significance was underscored on 3 October 1985, when the FST was designated a National Historic Landmark.

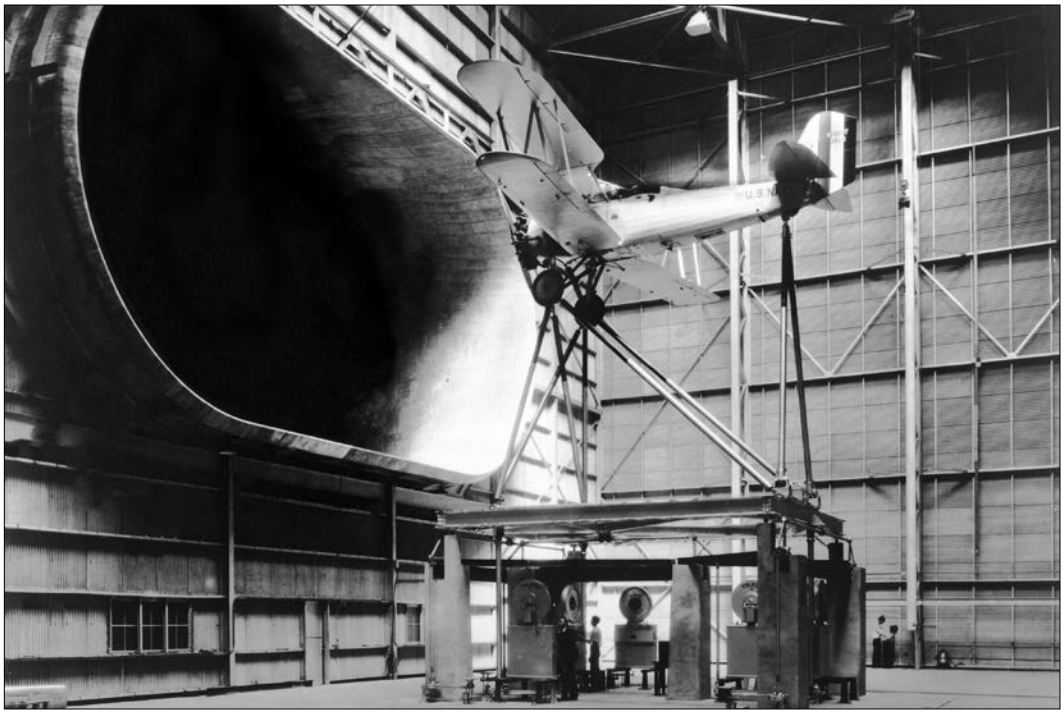
Since World War II, the FST has been overshadowed by the National Full-Scale Aerodynamics Complex (NFAC) at NASA's Ames Research Center, which is both larger and faster than the FST, and its future is uncertain. NASA officially closed the tunnel in October 1995, but it saw something of a second life when Old Dominion University began operating it in 1996, primarily to study the aerodynamics of land-based vehicles, including race cars for NASCAR teams. Old Dominion's lease expired in August 2009, and NASA, having allocated funds for its demolition, chose not to renew the lease. Ironically, the final test program in the FST, NASA's oldest wind tunnel, involved an aircraft on the cutting edge of aeronautical development, a blended wing-body transport concept that is still years away from flight.

As part of NASA's decision to remove deteriorating structures that do not have foreseeable mission applications, the FST was demolished in 2010. Its National Historic Landmark designation was removed in August 2014.

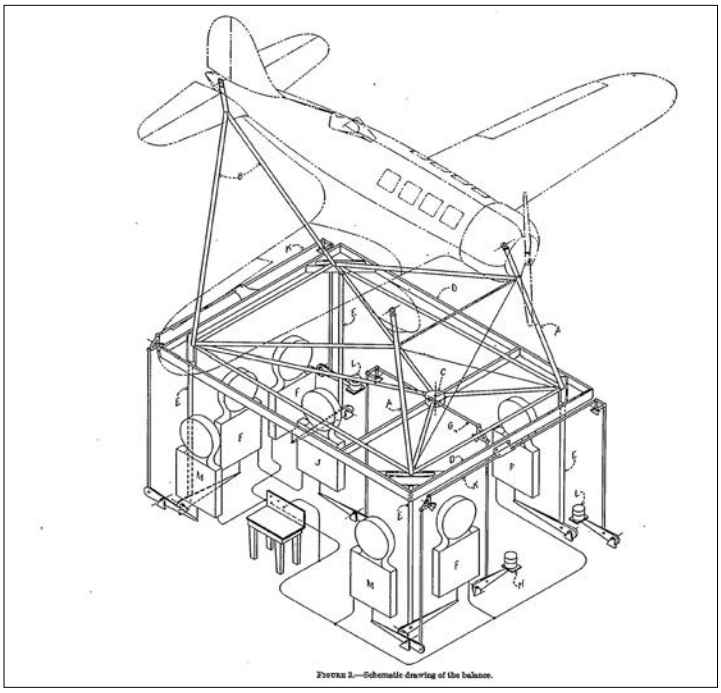


Isometric (top) and plan (bottom) drawings of the Full-Scale Tunnel, with a full-scale airplane mounted 34 feet above the floor, give a sense of the tunnel's immense size. Offices with 8-foot ceilings fill the area under the right end of the tunnel. (Image credits: NASA HAER VA,28-HAMP,4A and NASA CR-111868, Fig. 1)

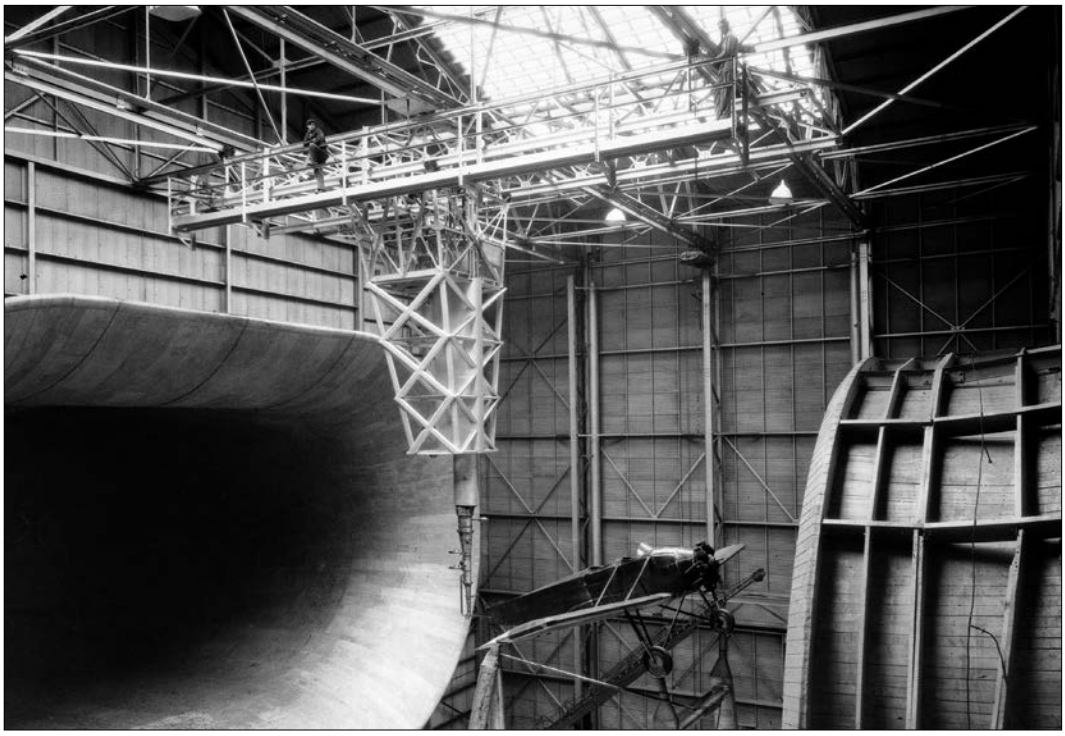




The Full-Scale Tunnel's 30- by 60-foot nozzle, test section, and balance, with a Vought 03U-1 mounted for testing in 1931. The balance room was enclosed after initial testing, and the balance remains intact, but the mechanical system and scales have not been used in recent years, having been replaced by more modern instrumentation. (Photo credit: NASA LRC-1931-B701_P-05553)

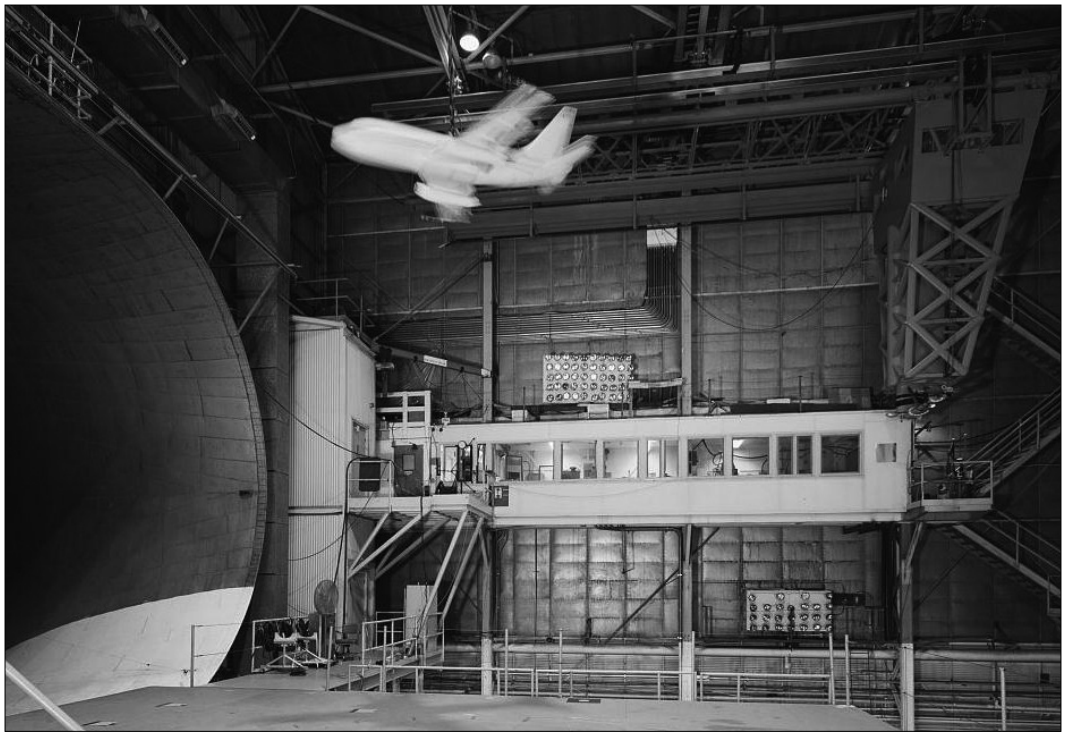


This diagram shows how the balance mechanism transmitted aerodynamic forces to the seven scales. One button on the control panel triggered printers on the scales to record their readings simultaneously. (Image credit: NACA Report No. 459, Fig. 3)

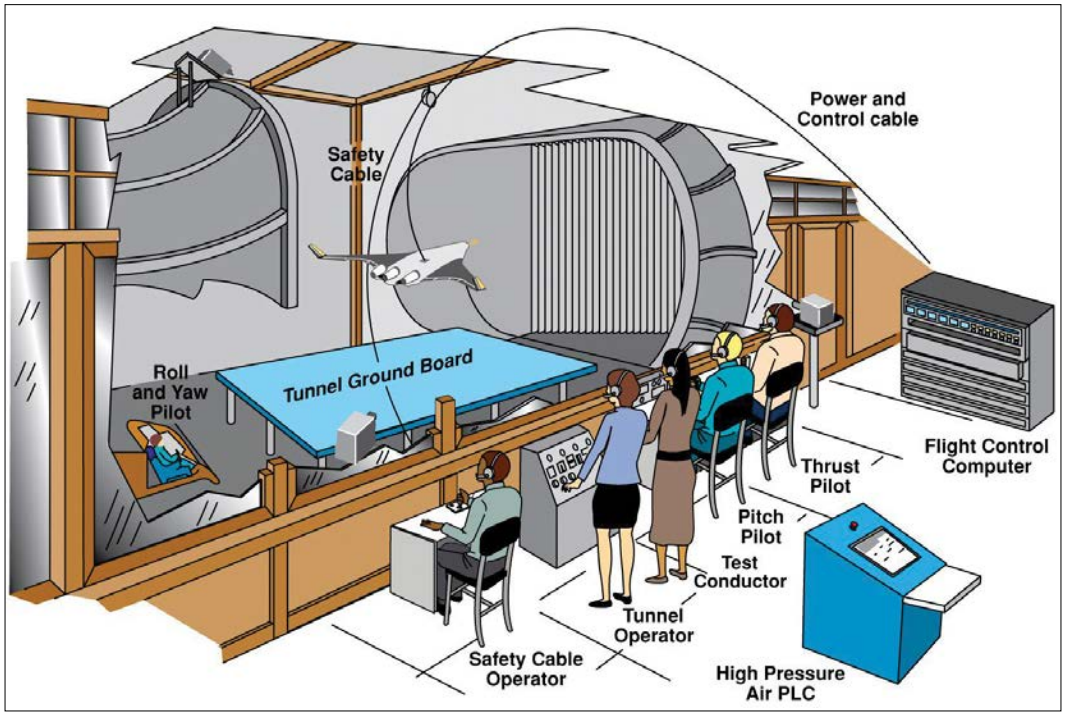


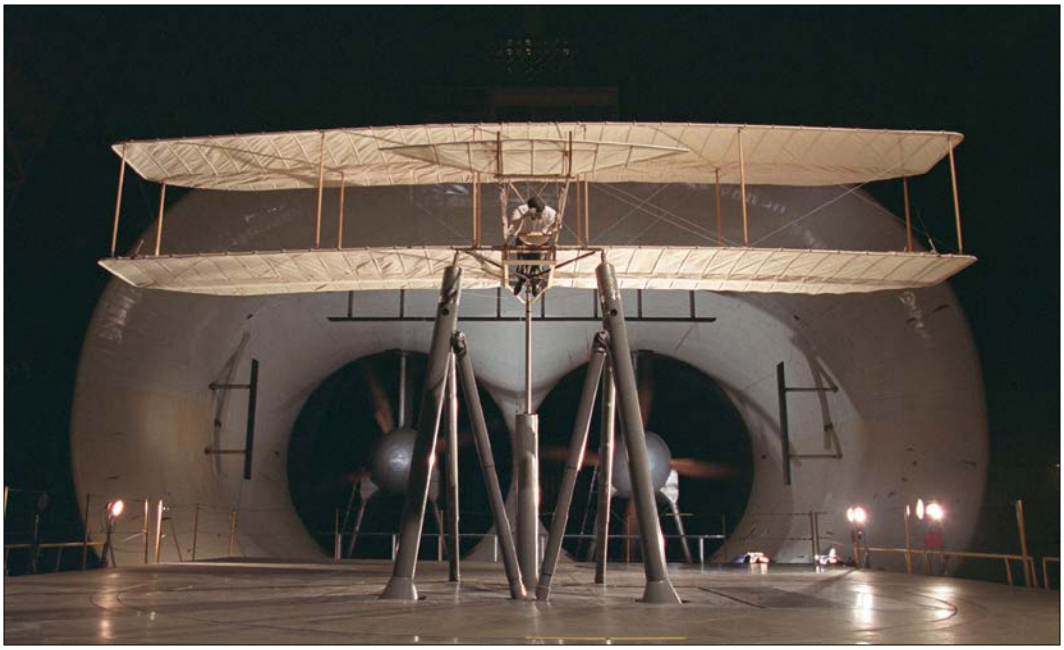
The Full-Scale Tunnel's survey apparatus and bridge in 1933. During test runs, this apparatus could move probes mounted on it in all directions to obtain readings at almost any point near the airplane to give researchers a complete map of the airflow parameters. (Photo credit: NASA LRC-1933-B701_P-08212)

A full-sized, boilerplate Project Mercury spacecraft being set up for testing in the Full-Scale Tunnel, January 1959. (Photo credit: NASA LRC-1959-B701_P-00336)

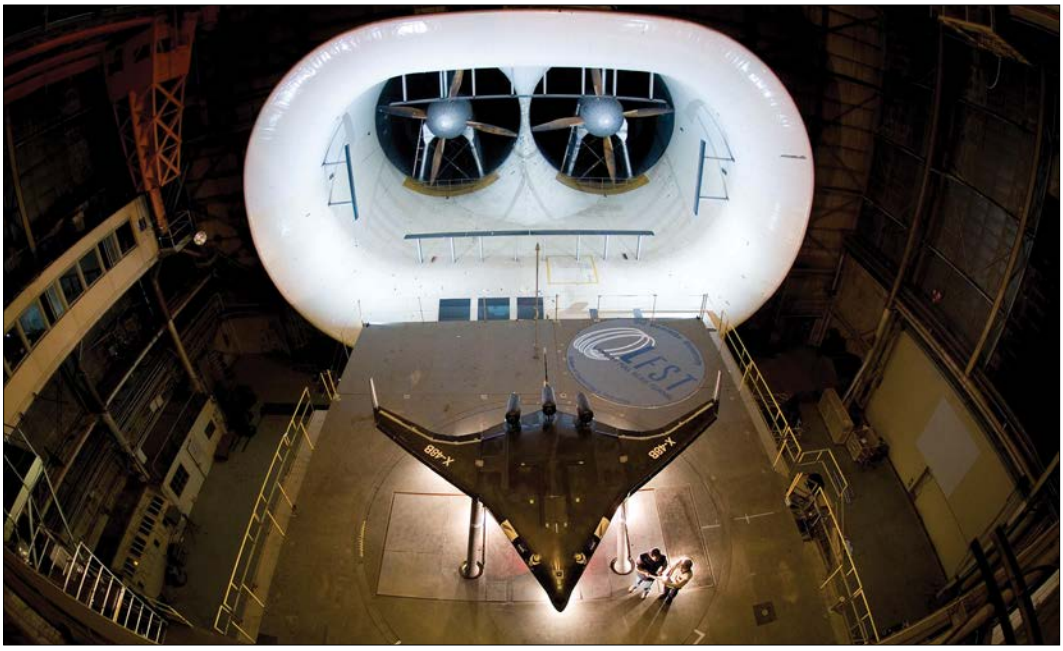


In the 1960s, free-flight testing of remotely controlled models in the Full-Scale Tunnel, using equipment installed on a balcony in the test chamber (top), evaluated the low-speed flight characteristics of several high-performance designs. The drawing (bottom) shows the equipment and operators required for these tests. Compressed air provided the model's thrust. (Photo and Image credit: NASA HABS VA-118-A-11 and NASA TM-2006-214501, Fig. 2)





Tests conducted in the Full-Scale Tunnel since 2000 covered the full spectrum of aviation, from a replica of the Wright brothers' 1902 glider (top) to one of the latest blended wing-body transport concepts (bottom). (Photo credits: NASA LRC-2003-H1_P-10-33a_1902 Glider and NASA ED06-0070-2)



24-INCH HIGH-SPEED TUNNEL

The 24-Inch High-Speed Tunnel sat adjacent to the original wind tunnel building (right) and the Variable-Density Tunnel building (behind) in 1934. The high-pressure air supply pipe and access walkway from the VDT building are hidden by the stack. The 24-Inch High-Speed Tunnel's control panel was inside the Variable-Density Tunnel building. (Photo credit: NASA LRC-1934-B701_P-09856)

SIGNIFICANCE

The 24-Inch High-Speed Tunnel (24-Inch HST) was the NACA's second wind tunnel capable of speeds close to the speed of sound (Mach 1), and it allowed Langley researchers to significantly expand their investigations into the complex aerodynamics that occur near Mach 1. Like the 11-Inch HST it replaced, the 24-Inch HST used compressed air from the Variable-Density Tunnel (VDT) as its power source. Built outside of a building, the 24-Inch HST featured an enclosed test chamber to house the NACA's first schlieren optics system to made shock waves visible. As newer tunnels assumed its initial role, engineers modified the 24-Inch HST no fewer than three times to suit other research needs in an inexpensive manner.

DESCRIPTION

The 24-Inch HST was essentially an enlarged version of the 11-Inch HST, but it was constructed outside, adjacent to the first Langley wind tunnel building and the one housing the VDT and 11-Inch HST. Being over twice the size of its predecessor, the 24-inch HST's flared steel exhaust stack reached 60 feet above the ground, well above the surrounding roofs. Completed in 1934, its outward appearance was of two stacked concrete cylinders. The lower cylinder, 31 feet in diameter and 10 feet high, formed an air intake and foundation for the test chamber. The 15-foot-diameter, 8-foot-high upper cylinder served as the test chamber, with the 24-inch-diameter steel test section rising vertically along its centerline. The test chamber was supported by six radial, concrete baffles in the lower cylinder that also served as guide vanes to direct air to the central entrance bell of the test section. The annular space between the test chamber and the lower cylinder's outer wall was open on top to admit the large flow of air but covered with a grate for safety. Access to the test chamber was from the mezzanine of the VDT building. An open steel walkway ramped down to the foot of the test chamber, where a steel door, the structure's only wall penetration, opened outward.[43]

A sheet-metal exhaust duct extended vertically from the top of the test chamber, braced with six struts. Part of the exhaust nozzle, it flared from a diameter of 36 inches leaving the test chamber to 78 inches at its outlet to the atmosphere. Two semicircular doors, operated by ropes down the side of the stack, closed the top when the tunnel was not in use.

An air supply pipe from the VDT reached the top of the test chamber through a steel pipe over the walkway. It was connected to the annular nozzle embedded in the test chamber roof at the base of the exhaust stack.

A 1949 modification substantially changed the tunnel. The exhaust stack was shortened to 48 feet, and a cylindrical steel enclosure measuring approximately 30 feet in diameter (at its base) by 54 feet in height was erected around the tunnel. The enclosure tapered slightly inward toward its peak, and it featured eight vertical stiffening ribs around its exterior. A circumferential cowl around its base provided weather protection for pressure-equalization vents. A single steel door in line with the test-section door provided normal access, although another removable panel was available for maintenance access. This enclosure changed the 24-Inch HST into a closed-circuit tunnel. It has, at least in recent years, been painted a medium-brown color.

HISTORY

The 11-Inch HST had shown that a wind tunnel using high-pressure air to induce a near-sonic velocity was practical, but the tunnel's small size rapidly proved very limiting. Eastman Jacobs, John Stack, and other members of Jacobs's group wanted to test larger airfoils. Stack had also accepted a recommendation from Jacobs and assembled a schlieren optics system to visualize what Stack called the "compressibility burble."

The crude system worked in the 11-Inch HST, but Stack needed a larger, vibration-free tunnel with more room around it for the schlieren system to function properly.[44]

To meet these needs, Jacobs and Stack, joined by engineers Ira Abbott, Walter F. Lindsey, and Kenneth Wood, designed the 24-inch HST during 1933. It operated like the 11-Inch HST, using high-pressure (starting at 300 psi) air from the VDT Tank flowing rapidly through an annular nozzle just above (downstream of) the test section. This generated a partial vacuum in the larger nozzle's throat, which induced a larger flow of atmospheric air through the test section. Like its predecessor, the 24-Inch HST could produce flow velocity of Mach 1 with the test section empty, although with shorter run times because of the faster consumption of VDT air.[45]

Since the conversion to a closed test section had been successful in the 11-Inch HST, the team incorporated one into the new tunnel from the beginning. The balance mechanism and model supports were similar to those developed for the earlier tunnel, albeit larger, but the camera to record measurements was not usually necessary. Since propeller blades remained the primary interest, high-speed airfoils would be the main test subjects, and the primary data needed were pressures at various points on the airfoil and schlieren photographs. Pressures could then be compared to the locations of shock waves and used to aid in the development of useful theory.

While the proportions of the 24-Inch HST were very similar to those of its predecessor, the new tunnel had a very different appearance. The larger size forced it outside the VDT building and necessitated stronger construction. While steel might have seemed to be the first choice for the tunnel, it was being built during the Great Depression, and steel fabricators were relatively rare. Additionally, the Public Works Administration decided to contribute $10,000 to the project as part of its program to put people, many of whom had few craft skills, to work. Accordingly, the designers elected to make the air inlet/foundation and test chamber of reinforced concrete, which could be built inexpensively by local people. Only the core portions of the tunnel would be of steel.[46]

The design ended up being a coaxial structure around a vertical centerline, giving the external appearance of one concrete cylinder stacked on top of a larger one with a long flared stack on top of that. Access to the test chamber was via a steel ramp from a door cut into the VDT building at its mezzanine level, and the air supply pipe ran approximately 8 feet over the ramp. The pipe turned down to supply the annular nozzle ring embedded in the roof of the test chamber, and it was equipped with a motor-driven valve.

Since the vacuum in the test section would also draw a vacuum on the test chamber, its wall, roof, and floor were approximately 1 foot thick to withstand the inward pressure of the atmosphere. Also because of the vacuum, the tunnel was designed for remote control operation so that operators could remain outside during test runs.

The two main types of apparatus initially used in the 24-Inch HST, a 60-tube photo-recording manometer and the schlieren optics system, were installed inside the test chamber. The manometer tubes were connected to orifices drilled in the model, and it used a neon flash tube to expose photosensitive paper behind the tubes. A small drive

advanced the paper after each flash. The schlieren system Jacobs and Stack designed was based on a system devised by German scientist August Töpler in 1864. In its simplest form, light from a source is collimated by a lens and passed through the test section to a second lens on the other side. That lens focuses the beam through a focal point to a screen. A knife-edge is aligned precisely at the focal point. With no density changes in the test-section air, the image on the screen will be clear, except for a silhouette of the model. At high airspeeds, however, air compresses, increasing its density, at various points around the model. This higher-density air refracts the collimated light at those locations, which causes those parts of the beam to strike the knife-edge while the remaining light passes over it to the screen. The result is an image with dark lines at high density (i.e., shock regions). Similarly, low-density regions will appear brighter.

To capture the schlieren images on film inside the test chamber, the team set up an 8- by 10-inch camera without its lens and with its shutter close to the knife-edge. Using an electric shutter release, an operator could press one switch that simultaneously clicked the shutter and flashed the manometer light. With images and pressure readings matched in time, the researchers had a way to see and begin to understand how shock waves developed and propagated.[47]

A typical test used an airfoil machined from duralumin and brass with a 5-inch chord and a 30-inch span. As in the 11-Inch HST, the wing extended beyond the test section walls, where it was mounted to either the balance yoke or a fixed yoke. After all preparations had been made, the researchers left the test chamber, closed and dogged down the door, and ran the test from outside. The motor-driven valve allowed the operator to adjust the air speed, and the remote-controlled instrumentation and camera helped keep test runs short. As with the smaller HST, multiple tests could be run before the VDT's air pressure fell to a useless value.[48]

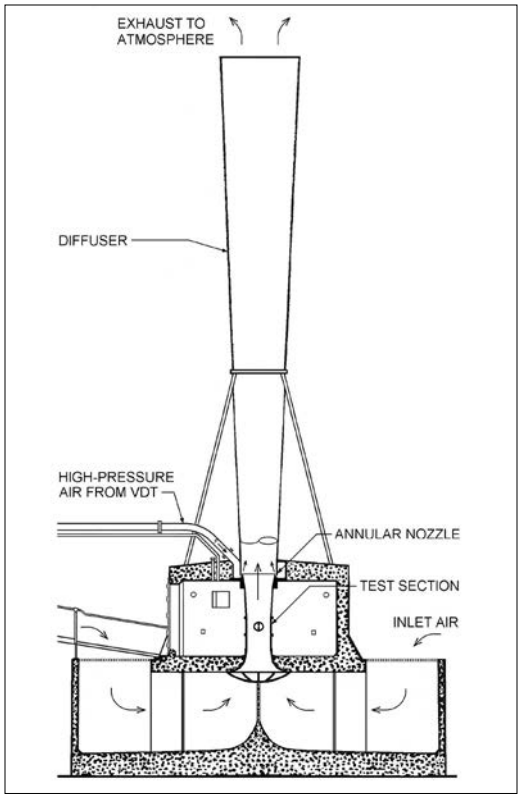
While the initial test programs in the tunnel involved airfoils for high-speed propellers—supersonic airplanes were not yet under development—the understanding of compressibility gained in the 24-Inch HST led to major improvements in high-speed wing design. This knowledge proved to be especially useful during World War II, as piston-engine fighters pushed beyond 400-mile-per-hour speeds and compressibility effects began to affect their performance.

The 24-Inch HST's test section was always closed, but in 1944 it was modified with two flat plates to give the test section two parallel walls 18 inches apart. This modification resulted from a concern that the tunnel's wall might be introducing a constriction effect that affected the results of some tests. To evaluate this, Robert W. Byrne needed a test section with parallel walls, so he modified the tunnel. His tests confirmed that the walls introduced significant constriction effects at high speeds. The 24-Inch HST retained this modification for the remainder of its life.[49]

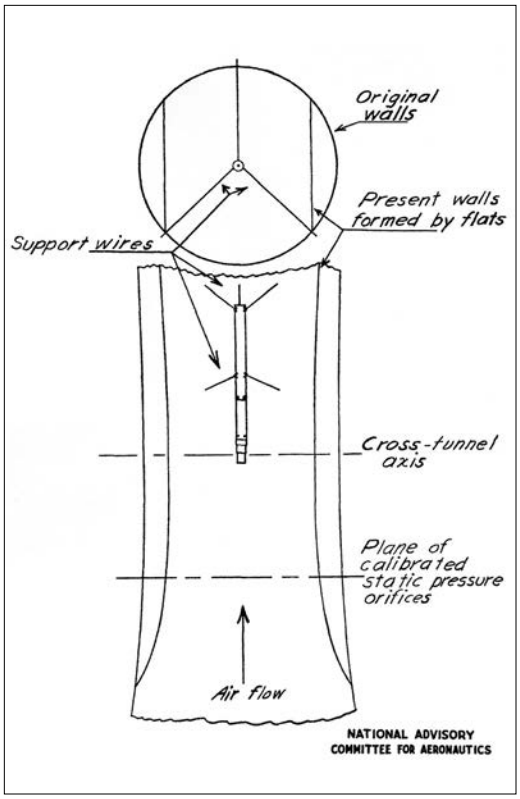
As aircraft speeds continued to increase after World War II, the tunnel remained a useful asset. With well-known characteristics, it was particularly useful for running high-speed pitot tube calibration studies.[50]

In 1949, Langley engineers installed a cylindrical metal enclosure around the 24-Inch HST in an attempt to reduce a chronic water condensation problem, which changed it into a closed-circuit tunnel. They shortened the exhaust stack by 12 feet at the same time to reduce the enclosure size and improve the tunnel's performance. Movable louvers near the bottom of the enclosure vented a volume of air to the atmosphere equal to the volume of induction air to maintain a constant volume of circulating test air. The tunnel remained in service in this configuration until 1952, when it received a slotted-wall test section for transonic testing and was renamed the 22-Inch Transonic Tunnel.

The 22-Inch Transonic Tunnel operated for 14 years until it was closed in 1966. In 1971, the tunnel was again rebuilt, emerging as the 6- by 19-Inch Transonic Tunnel. Except for instrumentation and control upgrades, these conversions involved little more than the installation of new test sections. The 6- by 19-Inch Transonic Tunnel remained in service until sometime in the 1990s, when it was closed as a cost-saving measure. Now in its fourth incarnation, this historic tunnel remains in place essentially intact.[51]



This section drawing of the 24-Inch High-Speed Tunnel shows how high-pressure air from the Variable-Density Tunnel induced a flow of outside intake air through the test section. The test section functioned like the throat of a converging-diverging nozzle, with the diffuser serving as the diverging portion. The combined flow originally exhausted to the atmosphere. (Image credit: NACA Report No. 646, Fig. 1)



With this 1944 modification that installed two flat walls in the test section, Robert Byrne was able to determine how the walls constricted the flow through the tunnel at high speeds. The flat walls were 18 inches apart at the cross-tunnel axis. (Image credit: NACA Wartime Report MR-L6A08, Fig. 2)

15-FOOT VERTICAL SPIN TUNNEL (FREE-SPINNING TUNNEL)

Building 646, seen here in 1981, housed the 15-Foot Vertical Spin Tunnel, and it later housed a variety of other equipment and activities as well. In the background, note the 12-Foot Free-Flight Tunnel (L) and the Full-Scale Tunnel (R). (Photo credit: NASA LRC-1981-B701_P-03500)

SIGNIFICANCE

The 15-Foot Vertical Spin Tunnel (15-Foot VST), also known as the Free-Spinning Tunnel, was the NACA's second wind tunnel built specifically to study the spinning characteristics of airplanes and its first to have models fly freely without any hard attachment to the tunnel. The 15-Foot VST differed markedly in concept from its predecessor, the 5-Foot Vertical Wind Tunnel, in that its airflow was upward. This allowed the models to be free-flying, supported solely by the airstream within the test section, and the models could be large enough to incorporate simple, preconfigured control devices to affect spin recovery.

DESCRIPTION

The 15-Foot VST was, like many of the NACA's early tunnels, erected as a stand-alone device inside a building. This building, originally numbered 193-A (now 646) in the East Area, was built next to the Full-Scale Tunnel in 1934 specifically to house the 15-Foot

VST—though it later hosted other facilities, including the 5-Foot Free-Flight Tunnel, and became known as the Dynamic Tunnels Building. The 15-Foot VST was erected in the west quadrant of the building, where a high bay reached to the roof trusses. The remainder of the building was divided into four floors of office, shop, and mechanical spaces that supported the operation.

The 15-Foot VST was designed to have upward vertical airflow through a semi-closed test section, which gave the entire tunnel a vertical orientation. The dodecagonal test section, measuring 15 feet between parallel walls and located approximately 20 feet above the floor, was surrounded by an enclosed wooden test chamber about 4 feet wide. This provided space for the test personnel and their equipment, primarily still and movie cameras and tools to release models. Six of the 12 test-section walls were glass, with the two central panels hinged. The opposite six walls were painted flat black to contrast sharply with the light-colored models used in tests. Lights above the glass panels illuminated the models for observation and photography, and a net below caught the models after a successful spin recovery dive or at the end of the test.[52]

A propeller at the top of the tunnel, driven by a 150-horsepower, DC electric motor, generated air speeds of up to 40 mph. The DC motor allowed technicians to rapidly and precisely adjust the fan's speed as necessary to obtain an airspeed that exactly matched the descent speed of any particular spinning model. Once in equilibrium, the model appeared to spin in place, making observation and photography easy.[53]

This tunnel was built as an open-circuit tunnel with some constriction through the test section. It drew room air in through five horizontal screens near the floor and exhausted it vertically toward the room's ceiling. The high-bay room served as the return duct. This made the 15-Foot VST easy and inexpensive to build—not including the building—but it compromised the tunnel's efficiency. Only 25 percent of the motor's power was actually realized in the air stream. Subsequent spin tunnels would be closed-circuit designs.

HISTORY

Airplane spins had been a problem since aviation's earliest days, and the problem remained serious and poorly understood three decades after the Wright brothers' pioneering flight in 1903. Researchers at both the NACA and England's Royal Aircraft Establishment in Farnborough had performed some perfunctory tests by dropping models approximately 100 feet inside balloon sheds. The technique showed promise, but there were too many unknown factors for the researchers to have much confidence that what they saw actually resembled the behavior of a full-sized airplane. Additionally, the limited vertical space available resulted in short test flights, and the 100-foot climb to reset the model meant long turnaround times. Teams in both Farnborough and Langley began searching for a wind tunnel design that would be useful for studying spins.

Langley engineer Charles H. Zimmerman first tackled the problem by building the 5-Foot Vertical Wind Tunnel (5-Foot VWT). It held the spinning model on a powered,

rotating balance within a *downward* flowing column of air, with the primary objective being to measure aerodynamic forces acting on the model during preset spinning motions.[54]

Meanwhile, the British researchers built a small, vertical tunnel to test the concept of having a free-spinning model supported only by a column of air. The idea proved to be sound, so they built the first permanent free-spinning tunnel, with a 12-foot diameter, in 1932. It was large enough to accommodate models with wingspans of up to 3 feet, and these were large enough to be adequately accurate without having to maintain impracticably close tolerances.[55]

The advances in understanding of the spin problem provided by research in the 5-Foot VWT, coupled with reports of the British success, led Zimmerman to propose that the NACA build a similar spin tunnel at Langley. While the rotating balance in the 5-Foot VWT had been successful in analyzing the role of certain aerodynamic phenomena in spins, he believed that the force and moment data obtained from that balance paled in significance to the more qualitative information his team gained through careful observation of a model's dynamic behavior during spins and its response to control surface changes. In a free-spinning tunnel, the model would be able to fly completely free from interference from any mechanical support and, thus, replicate actual performance very closely and produce results in a timelier manner than theoretical studies. Still photographs and movies would serve as the primary test records and allow repeated analysis of any test after the fact.[56]

The NACA approved Zimmerman's proposal in June 1933, and he began working on the design immediately. Construction was completed in September 1934, and the tunnel officially went into service after calibration tests in April 1935. As with some other early NACA tunnels, records of the date of deactivation and demolition of the 15-Foot VST seem to have been lost, but it appears to have been in service throughout World War II, and a 1961 Langley telephone directory lists a "Vertical Tunnel" in Building 193-A.

The models flown in the 15-Foot VST, classified as "dynamically scaled models," were unlike most wind-tunnel models. In addition to geometrically scaled surfaces, the model's weight and mass distribution had to be designed following strict scale parameters based on the full-scale airplane's features in order to mimic the dynamic motions of that airplane. For single-engine planes of the era, most models were built to 1/10 or 1/16 scale, which resulted in wingspans between 2.5 and 3 feet. Balsa wood was the preferred material because of its low density, but key areas like the leading and trailing edges of wings had to be reinforced with stronger woods to avoid damage from contact with the walls or net. Portions of the wings and fuselage were hollowed out to allow proper mass distribution and provide space for control mechanisms. These areas were then covered with silk tissue paper, and the entire model was shellacked. Fortunately, these models could be built to wider dimensional tolerances than most fixed wind-tunnel models with no detrimental effects on the tests.[57]

A model's mass distribution was determined by the classic method of swinging it as part of a compound pendulum and timing the oscillations. The team built a frame for

this that was itself supported by the bottom head of a vacuum chamber. Unless much was known about the dynamic characteristics of the full-sized airplane, these swing tests were run under a vacuum to eliminate air resistance. Moments of inertia about all three axes then could be calculated and lead weights added as necessary to replicate the airplane's scaled mass distribution.[58]

A model was launched by placing it on the end of a hand-held pole with a small spindle on its end. Each model had a small recess so that its center of mass rested on the spindle. The model was then inserted into the center of the tunnel, with its rudder having an initial pro-spin deflection, and the fan started. As the tunnel came up to speed, the model started to rotate on the spindle, and it lifted off into spinning free flight as soon as the air flow fully supported it. The launching process took only a few seconds, and the model usually assumed a consistent spin almost immediately.[59]

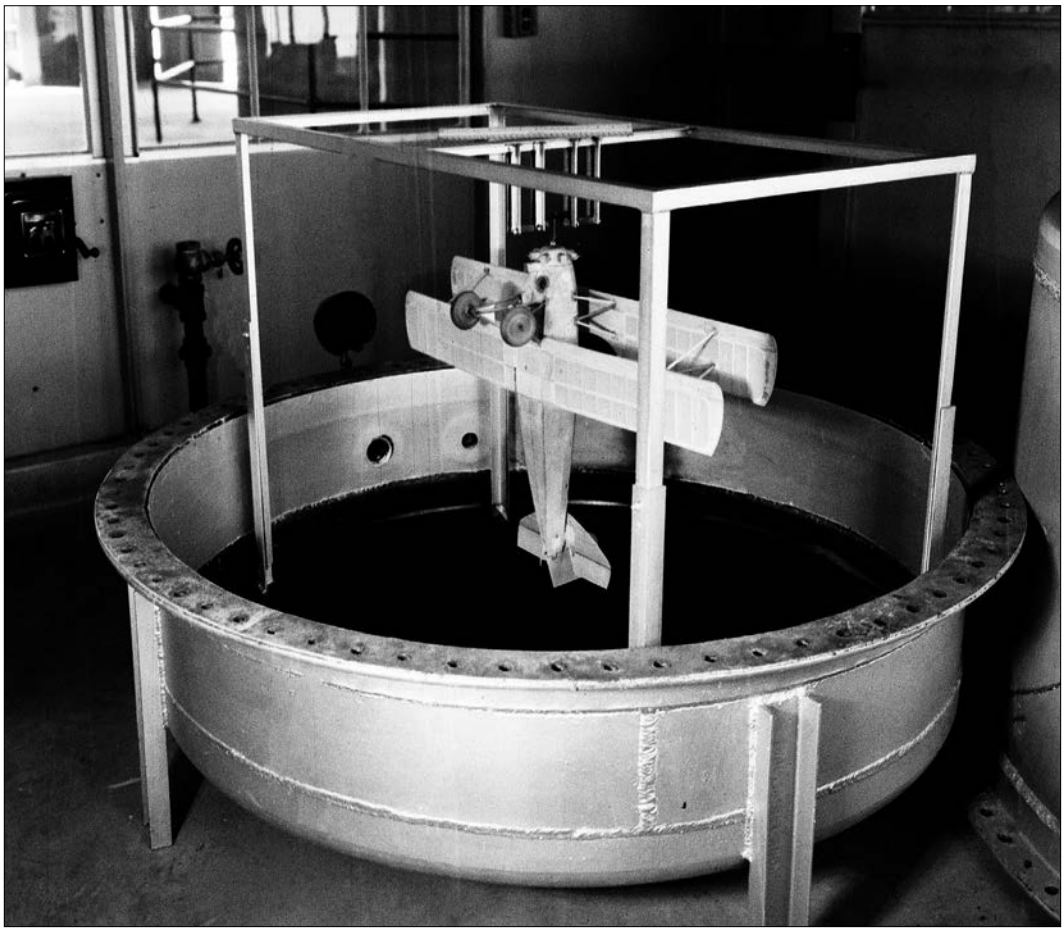
To evaluate a model's spin-recovery performance, Zimmerman's team developed a spring-driven mechanism that drove three cam disks to perform a pre-configured sequence of control surface actuations. This was timed to start after a stable spin had been achieved, and the device released a small flag to indicate when it began the recovery sequence. A successful recovery ensued when the spinning motions were terminated by the recovery controls and ended with a dive into the catch net. If the test did not include a recovery sequence, slowing the fan allowed the model to settle gently into the catch net, or a technician could catch a spinning model in a handheld net.[60]

Some of the earliest tests in the 15-Foot VST compared the spin performance of XN2Y-1 and F4B-2 models with the known performance of their full-sized counterparts. The results were mixed, with each model's performance in spins and recoveries better than its prototype in some situations and worse in others. Nevertheless, these early tests were encouraging enough to warrant further experimentation, and Zimmerman's team soon refined their techniques to produce consistent results. Their research into various stall-recovery techniques led the NACA to recommend a four-step recovery procedure that became known as "PARE," a mnemonic for **P**ower at idle, **A**ilerons neutral, **R**udder held opposite the spin, and **E**levators moved through neutral to reinstate level flight. First issued in 1936, PARE remains a standard stall-recovery technique.

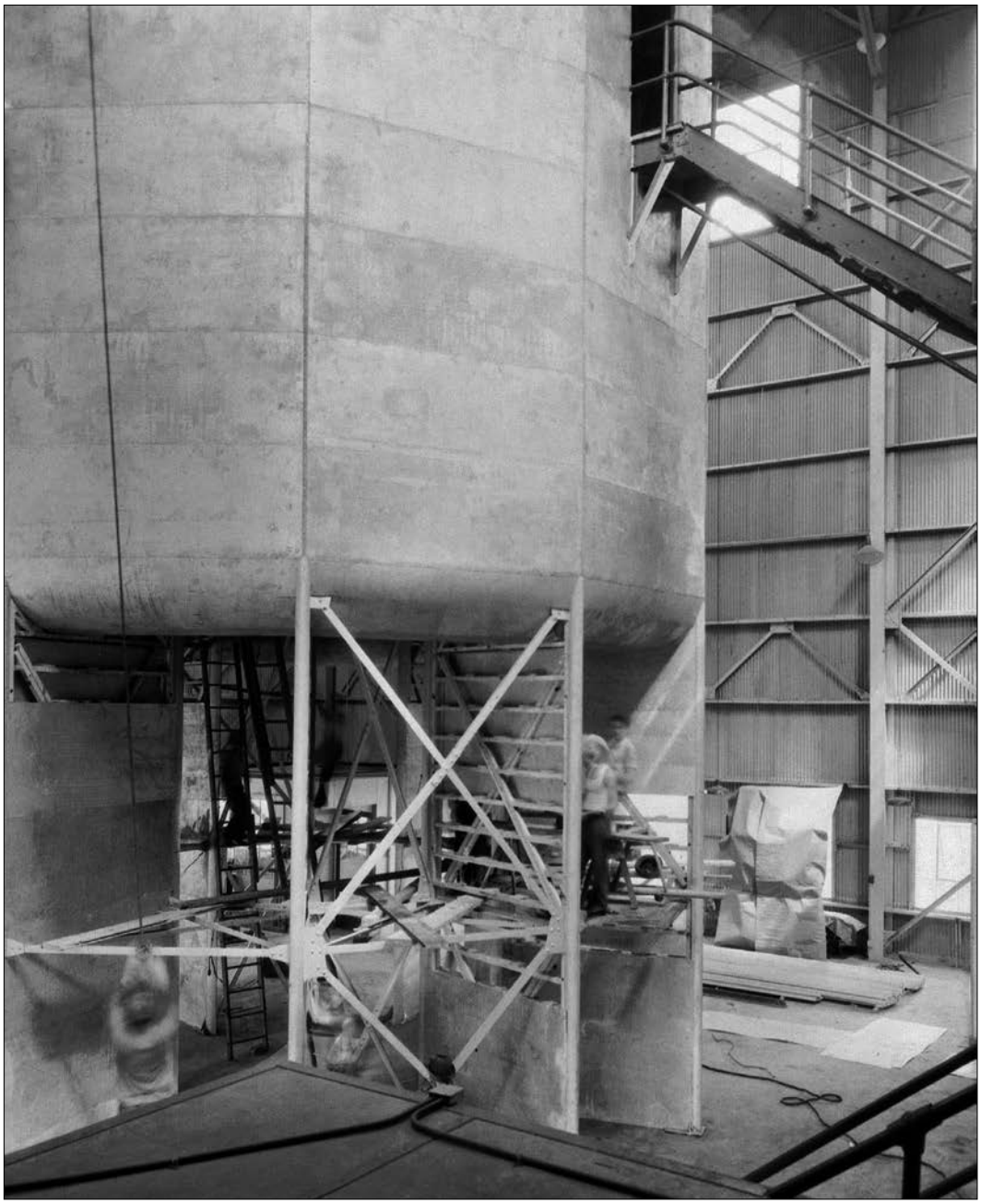
The 15-Foot VST was intended as a "pilot" tunnel to validate the free-spinning concept and inform the design of a permanent spin tunnel. It succeeded admirably in both roles, and the NACA soon approved construction of the 20-Foot Vertical Spin Tunnel that opened in 1941. But the 15-Foot VST continued in service throughout World War II, as more than 300 designs required spin testing during the conflict, a level of demand that kept both spin tunnels busy.

The final disposition of the 15-Foot VST remains somewhat obscure, but it has been gone for some time. The advent of much heavier military aircraft, the greater vertical speed capabilities of the 20-Foot VST, and the reduced demands of postwar developmental testing resulted in the 15-Foot VST becoming redundant for free-spinning tests after the war, and it was demolished during the late 1940s.

Building 646 has, however, seen a variety of uses since that time. In 1950, Langley built an apparatus reminiscent of, though much less expensive than, the Gust Tunnel in the space vacated by the 15-Foot VST. Known as the Catapult Model Apparatus, it consisted of a crude catapult that used a bungee cord to launch a free-flying model more-or-less horizontally from a location near the ceiling and a net to catch it near the floor. It was intended to explore the conditions that cause an airplane to leave normal flight and enter a spin. A researcher manually launched the model with a pre-set configuration and angle of attack, after which it would usually enter a spin and spiral down to the net, with the entire flight recorded on movie film for later analysis. These tests proved to be of little use, and the apparatus was soon discarded. During the 1950s, several types of vertical takeoff and landing concepts were evaluated in the high-bay space as well. In the early 1970s, a large air compressor was installed in the space. Building 646 still exists, housing the compressor, along with some shop and office areas, plus the 12-Foot Low-Speed Tunnel's Control Room, but no trace of the 15-Foot VST remains.[61]

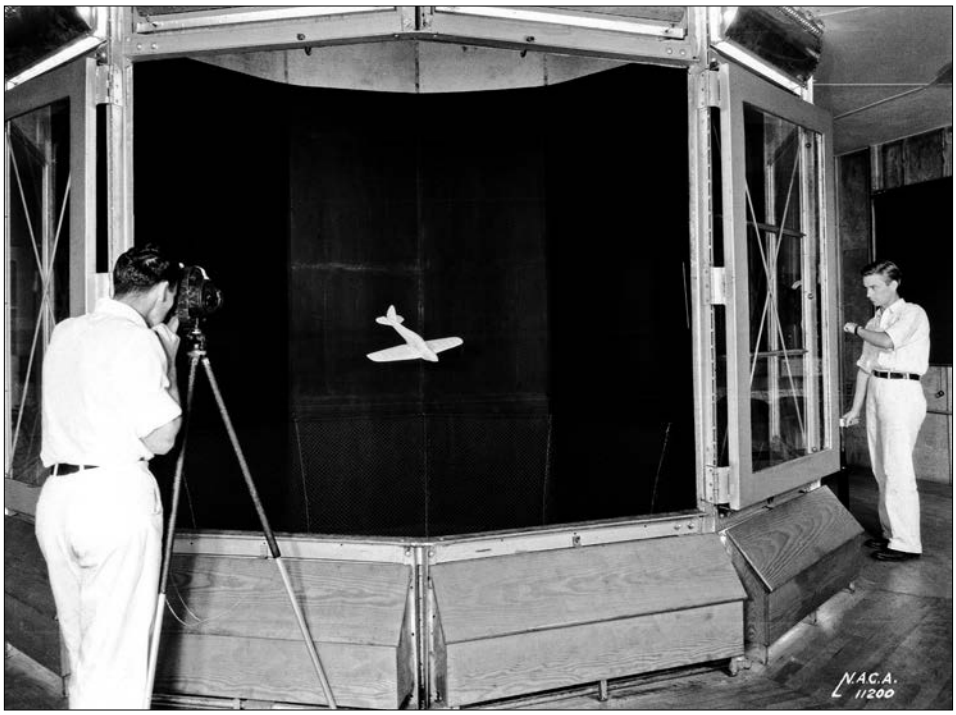


Balsa models were swung on this compound pendulum device to determine how to add weights and correctly simulate the prototype's mass distribution. Correct mass distribution was an essential element of simulating an airplane's dynamic behavior. To eliminate errors caused by air resistance, an upper shell was bolted to the flange to form a chamber that was then evacuated before swinging the model. (Photo credit: NASA LRC-1935-B701_P-11201)



This rare 1934 photo of the lower portion of the 15-Foot Vertical Spin Tunnel's exterior reveals how the tunnel was built as an independent structure within Building 646's high bay. Air was drawn into the tunnel between the support legs and up through a central passage containing the test section by a fan near the top, then discharged into the room, which served as the return plenum. Note the staircase up to the test chamber. (Photo credit: NASA LRC-1934-B701_P-10279)

These two views of the 15-Foot Vertical Spin Tunnel's test section in 1935 show a technician launching a model (top) and then filming it during the test (bottom). With the tunnel's air speed set to match the descent speed of the spinning model, it appeared to rotate in place, allowing detailed observations of its behavior in free flight. (Photo credits: NASA LRC-1935-B701_P-11199 and NASA LRC-1935-B701_P-11200)



8-FOOT HIGH-SPEED TUNNEL
8-FOOT TRANSONIC TUNNEL

The 8-Foot High-Speed Tunnel shortly after its completion in 1936. Note the Propeller Research and Full-Scale tunnels in the background. (Photo credit: NASA LRC-1936-B701_P_F001-11861)

SIGNIFICANCE

The 8-Foot High-Speed Tunnel (8-Foot HST), opened in 1936, is one of NASA's most historically significant facilities. It was the NACA's first large wind tunnel capable of speeds close to the speed of sound (Mach 1). It also represented an unusual partnership between the NACA and the Public Works Administration (PWA) when its construction provided Depression-era jobs. That partnership led to the 8-Foot HST being built with reinforced concrete instead of steel.

After being rebuilt with slotted test section walls in 1948, the 8-Foot HST became the first successful transonic (Mach 0.7–1.2) wind tunnel, finally providing a facility for investigation of this complex flight regime. It was the prototype for numerous transonic tunnels to follow. The tunnel was modernized further in 1953 with the addition of a semiautomatic electronic data-collection system, one of the NACA's early installations of such hardware.

The 8-Foot HST hosted investigations into a wide variety of high-speed topics, including swept wings, air intakes, propeller blades, bomb stability, and the dive-recovery flaps that saved many World War II fighter pilots from total loss of control. After its slotted-wall modification, the renamed 8-Foot Transonic Tunnel (8-Foot TT) most famously hosted Richard Whitcomb's work that produced the drag-reducing area rule used in the design of many jet aircraft.

The 8-Foot TT was at the center of two Collier Trophies received from the National Aeronautic Association by Langley people: first for the slotted wall test section in 1951, and again for the area rule in 1954. In further recognition of its importance to aerospace research, the tunnel was designated a National Historic Landmark by the Department of the Interior on 3 October 1985.

DESCRIPTION

The 8-Foot High-Speed Tunnel (Building 641) is located on the shore of Back River, immediately southwest of the Full-Scale Tunnel in Langley's East Area. The 8-Foot Transonic Pressure Tunnel is to its immediate northwest, although the Propeller Research Tunnel occupied that location when the 8-Foot HST was built.[62]

The 8-Foot HST was a closed-circuit atmospheric wind tunnel constructed almost entirely of reinforced concrete. It had a circular cross section throughout it length and was supported entirely above ground by legs cast integrally into the tunnel walls. Those at each of the four corners had a large ring that encircled the tunnel supported by two legs. Intermediate supports also had two legs, with gussets that flared tangentially into the tunnel walls. The 8-Foot HST's most distinctive feature was its test section enclosure shaped like an igloo. The unusual enclosure, with walls 1 foot thick, was designed to resist atmospheric air pressure, since the test section normally operated at a partial vacuum. A second identifying feature was the tunnel's air-exchange tower in the long return leg. Also concrete, this 53-foot-high rectangular tower had louvers near its top on all four walls. Half of these louvers exhausted heated air from the tunnel, and the other half drew in replacement air from the atmosphere. Operating on the venturi principle, this tower functioned without blowers during tunnel operation.

Overall, the 8-Foot HST measured 164 feet, 9 inches in length by 59 feet in width. Its inside diameter flared from 8 feet in the test section to 24 feet in the settling chamber, after which an entrance cone with a 9-to-1 contraction ratio necked down to the test section diameter. The circuit's walls varied in thickness from 6 to 12 inches. The test section retained its slotted-wall appearance, but without most of its hardware. Steel turning vanes were installed in each of the mitered corners. The tunnel's exterior was unpainted and weathered. Additionally, several places exhibited surface spalling, with some of them appearing to be the result of experiments in demolition techniques.[63]

A 35- by 52-foot masonry building that housed the tunnel's motor and other electrical equipment stood adjacent to the tunnel's northeast leg, and a two-story office and shop building stretched along most of the southeast side. There have been two additions to the office building, but they are similar in style to the original structure with prominent pilasters. Large windows occupy most of the space between the pilasters in groups of one, two, or four.

The tunnel was originally powered by an 8,000-horsepower AC electric motor coupled to a 16-foot-diameter, 18-blade fan located after the tunnel's second corner. Following a motor failure, a 16,000-horsepower (22,000 HP short-time rating) motor

was installed in 1945, along with a second fan to accommodate the increased power. A Kramer speed control, housed in an addition to the electrical building, replaced the original liquid-rheostat motor control, allowing better control and higher speeds. After the tunnel closed, its dual-fan assembly was removed and sent to Wright-Patterson Air Force Base for use in a new wind tunnel being built there.

HISTORY

The success of the 11-Inch HST prompted Langley's engineers to think about how such test speeds could be maintained for longer periods and about what it would take to build and operate a tunnel large enough to accommodate reasonably sized models of complete airplanes. Tests of components in the 11-Inch HST had already shown that the effects of compressibility were complex, and researchers suspected that the shock waves formed by different parts of an airplane might very well interact with each other. They needed a tunnel large enough to accommodate a model of a complete airplane with speeds high enough to generate these multiple shocks.

In the mid-1930s, Eastman Jacobs began to press for a high-speed successor to the VDT. While his idea came to fruition with the two low-turbulence tunnels, it was also the genus for what became the 8-Foot HST. Yet Jacobs played no other role in the design and construction of the 8-Foot HST, as his efforts were focused on the Two-Dimensional Low-Turbulence Tunnel at the time. Russell G. Robinson and Manly J. Hood, both young Langley engineers, led the design team. Authorization to proceed came from Washington in 1933, thanks to funds from the PWA, one of the early agencies established during the Franklin D. Roosevelt administration to combat the Great Depression. Design and construction took three years, and, thanks to the depressed economy, the NACA got a bargain, with the tunnel costing only $266,000.

Robinson and Hood calculated that a top speed of around 540 mph, or Mach 0.7, could be achieved in an 8-foot-diameter tunnel using an 8,000-horsepower motor. But as they ran through their design calculations for the new tunnel, two new problems loomed large. Ever since the effect was first discovered by Daniel Bernoulli in 1738, engineers and scientists had known that a gas in motion exerted a lower static pressure than one at rest, and that this "Bernoulli effect," as it came to be known, was proportional to speed. Calculations predicted that the test section static pressure would drop to something like 9.5 pounds per square inch absolute (psia), the equivalent of being at a 12,000-foot altitude. The difference between this and the atmospheric pressure of about 14.7 psi translated into the test section walls needing to withstand a differential pressure of almost 750 pounds per square foot of wall area. Robinson and Hood originally planned to build the tunnel with steel, but Depression-era economics pointed to reinforced concrete as a practical alternative. The PWA's primary goal was to put unemployed workers, many of them essentially unskilled, back to work, and just about anyone could mix and carry concrete or build the wooden forms with minimal guidance.

This was not the case with steel fabrication, which demanded specialized workers with a high degree of skill.

Concrete had been used before in the construction of wind tunnels, but relatively thin walls were employed because of the low pressure differentials expected. Such thin construction would not suffice for the 8-Foot HST, but thin test section walls were needed. To solve this problem, Hood and Robinson enclosed the test section in a larger pressure vessel so that there would be no pressure differential across the walls of the actual test section, allowing the walls and their windows to be thin. The pressure vessel took the shape of a giant igloo with walls 1 foot thick to withstand the pressure, but this design provided space around the test section for a control room and the balance apparatus. Everything inside the igloo, including the motor controls and balance scales, operated at test section pressure, so the operating personnel wore oxygen masks as a precaution against hypoxia during tests. An airlock enabled entry and exit during test runs.

The other new problem Robinson and Hood needed to overcome was heat buildup. As with the Bernoulli effect, engineers had long known that fans or propellers heat air passing through them. This is because a fan is actually an air compressor, though one designed to use its energy more to move a high volume of air than to achieve a high pressure differential. When a given volume of any gas is compressed, its temperature will rise according to the gas law, $pv = RT$, where p is pressure, v is specific volume, R is a constant for the specific gas, and T is temperature. In low-speed tunnels, the compression ratio across the fan is only slightly greater than 1 to 1, but this begins to increase noticeably above Mach 0.6. At the Mach 0.7 design condition for the 8-Foot HST, the compression ratio was greater than 1.1 to 1, enough compression to introduce considerable heat to the air. At full power, the 8,000-horsepower motor-fan combination would raise the air temperature in the tunnel by 10 degrees per second. To solve this problem, Robinson designed a heat exchanger—actually an air exchanger—between the fan and the test section. This unit, a louvered tower above the back leg of the tunnel, extracted approximately 1 percent of the fan's discharge air from the tunnel and discharged it to the atmosphere while simultaneously introducing an equal amount of cooler atmospheric air into the tunnel. Because of its venturi-like design, it performed this exchange without the need for additional fans. This small volume of air transfer effectively handled the excess heat, and the design has been used on many subsequent transonic and supersonic tunnels.[64]

The 8-Foot HST exceeded design expectations when it opened in 1936, producing a top speed of 575 mph (Mach 0.75), and it began to produce important results immediately. The first tests in it involved an examination of wing surfaces with typical damage that might result from cannon fire. These tests showed such a great increase in drag, compared to an undamaged wing, that Langley engineers and their counterparts in the aircraft industry began to look more closely at such things as the effects of button-head rivets and lap joints, then standard airplane construction details. Finding that these could increase drag by as much as 40 percent, they began to introduce designs with flush rivets and butt joints, features that became dominant during World War II.

Another significant program involved a controllability problem with some of America's newest fighters, including the P-38. For the first time, planes could reach speeds in dives high enough for compressibility to cause severe buffeting and even a total loss of control from which a pilot could not recover. The 8-Foot HST produced speeds high enough for the phenomenon to be observed and for corrective measures, such as the now-famous dive-recovery flap, to be validated. (Further development of the device transferred to the Ames Laboratory.)[65]

The 8-Foot HST, the first tunnel that was both large and fast, set a new standard for wind tunnel design, and it went on to experience additional "firsts." Repowered with a 16,000-horsepower motor after the original one failed in 1943, the tunnel reached speeds of Mach 0.99 when it reopened in 1945 before a phenomenon called "choking" occurred in the test section. Choking is a thermodynamic consequence that limits air speed to Mach 1 in the narrowest part of the tunnel—around the model in the closed test section. Swedish engineer Karl de Laval had achieved supersonic speeds with converging-diverging nozzles in steam turbines around 1890, and similar nozzles worked in wind tunnels above Mach 1.2. But the speed range between about Mach 0.7 and 1.2, known as *transonic*, was impossible to maintain in tunnels. It included a complex mix of localized sub- and supersonic velocities that neither subsonic nor supersonic tunnels could handle, yet this was a speed range where many new jets would fly.

In 1946, Langley physicist Ray H. Wright, looking to reduce the effects caused by shock waves reflecting off tunnel walls, proposed cutting slots in the test section walls. Wright's idea was based partly on theory dating back to the 1920s, but never demonstrated. Interestingly, the same theory suggested that slots might help reduce choking as well. Division Head John Stack supported Wright and fought considerable opposition to the conversion at Langley. Ultimately successful, Stack surprisingly announced that the 8-Foot HST would get the first slotted walls in spring 1948. Almost everyone had expected the newer 16-Foot High-Speed Tunnel to be the prime candidate.

The modified tunnel restarted late in the year, and it easily exceeded Mach 1. The flow was initially rather unstable, but Wright, assisted by Virgil Ritchie and Richard Whitcomb, methodically refined the shape of the slots over seven months until they obtained smooth flow throughout the transonic regime. In the process, Wright spent considerable time inside the igloo, which served as a plenum that contained air passing in and out of the slots, while the tunnel was running. The pressure, temperature, and noise conditions there required him to wear a hard-hat diving suit for protection. (The suit survives in Langley's archives.) Tunnel operators were not affected because the tunnel's controls had been moved outside the igloo.[66]

While it took some time to perfect the slotted wall, transonic research began in earnest during 1950. One of the NACA's first electronic data-collection systems was added in 1953. This semiautomatic system improved the accuracy and ease of manipulating the measurement data, and it helped pave the way for today's computerized data-management systems. The most famous test project in the renamed 8-Foot

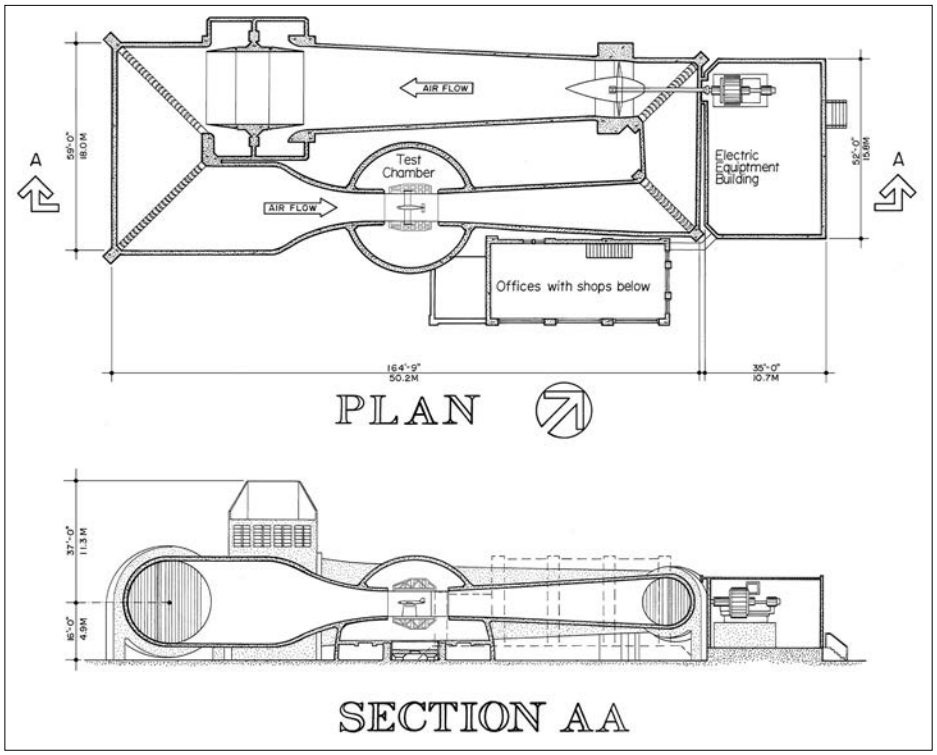
Transonic Tunnel (8-Foot TT) was undoubtedly Whitcomb's development of the area rule. By necking down an aircraft's fuselage where it met the wings, thus maintaining a nearly constant cross-sectional area, the drag of transonic and supersonic flight could be reduced almost 25 percent.[67]

The slotted wall made stable transonic wind tunnels possible, and the invention won the 1951 Collier Trophy for Division Head John Stack. It was truly a milestone in wind-tunnel development, and numerous transonic tunnels have been built on this model since. And using the remodeled tunnel to develop the area rule, Whitcomb won another Collier Trophy in 1954.

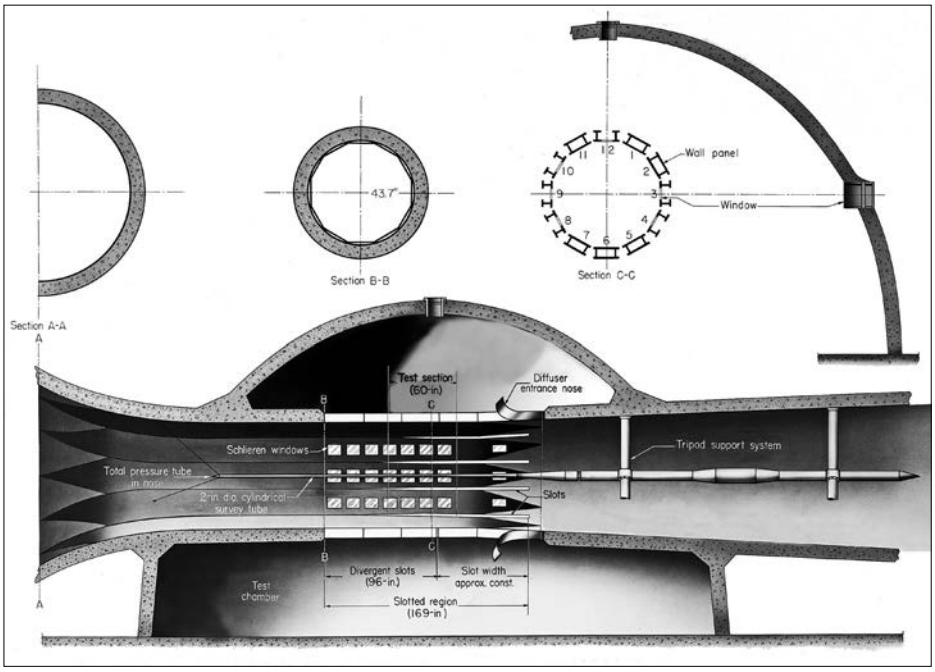
Though it had proven the slotted wall to be sound, the 8-Foot HST was not perfect as a transonic tunnel. Although it produced valuable research data, its operation revealed problems from high humidity, high turbulence, and low Reynolds number that could only be addressed in an all-new tunnel. After the 8-Foot Transonic Pressure Tunnel (TPT) opened in 1953, the 8-Foot TT's workload declined, and the NACA deactivated it in 1956. The massive concrete structure remains in place, and Air Force personnel now occupy portions of the office building. All key components of the test section have been removed. In the years since its deactivation, the fans were removed for reinstallation in an Air Force tunnel in Dayton, Ohio, so in one sense at least, a part of the 8-Foot TT lives on. On 3 October 1985, three decades after it closed, the tunnel was designated a National Historic Landmark in recognition of its extraordinary contributions to American aerospace.

NASA rehabilitated the office portion of the facility in the early 2000s and leased it to the Langley Air Force Base (permanently transferred in 2016). The tunnel circuit, however, remained abandoned and was demolished in 2011. The National Historic Landmark designation was removed in 2014.

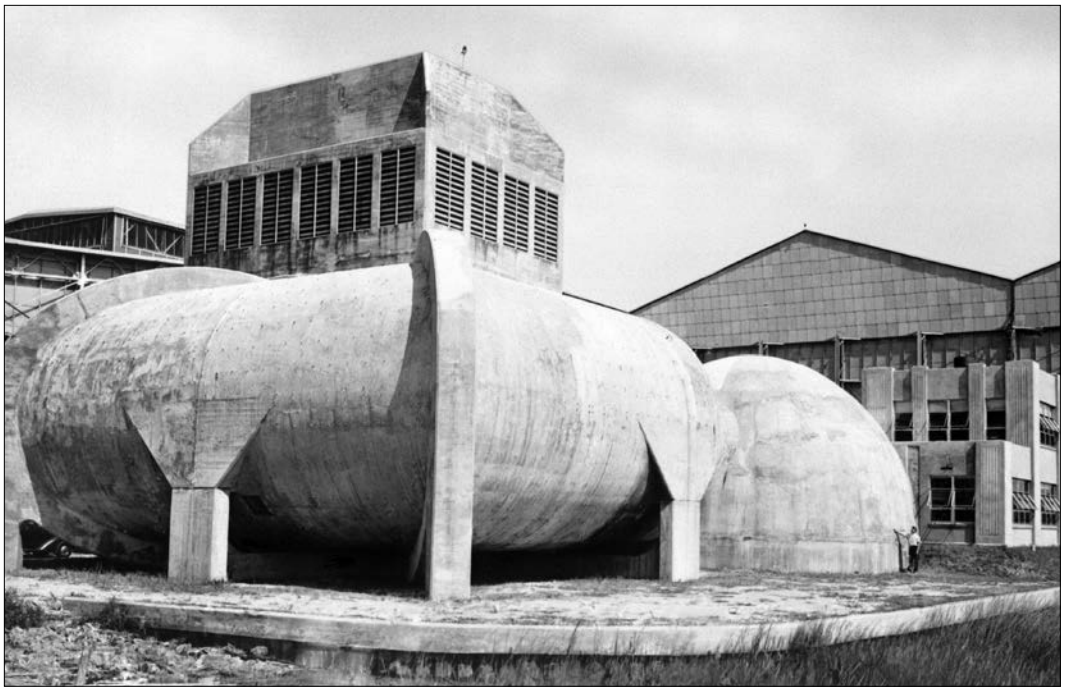
Ray Wright donning a deep-sea diving suit in 1950 to protect him from the harsh conditions inside the 8-Foot High-Speed Tunnel's plenum while he adjusted the test section slots with the tunnel operating. (Photo credit: NASA LRC-1950-B701_P-64110)



These drawings show the original configuration of the 8-Foot High-Speed Tunnel. Note the thick—as much as 1 foot in the igloo—reinforced concrete walls and the air-exchange ducts at upper left. (Image credit: NASA HAER VA-118-B)



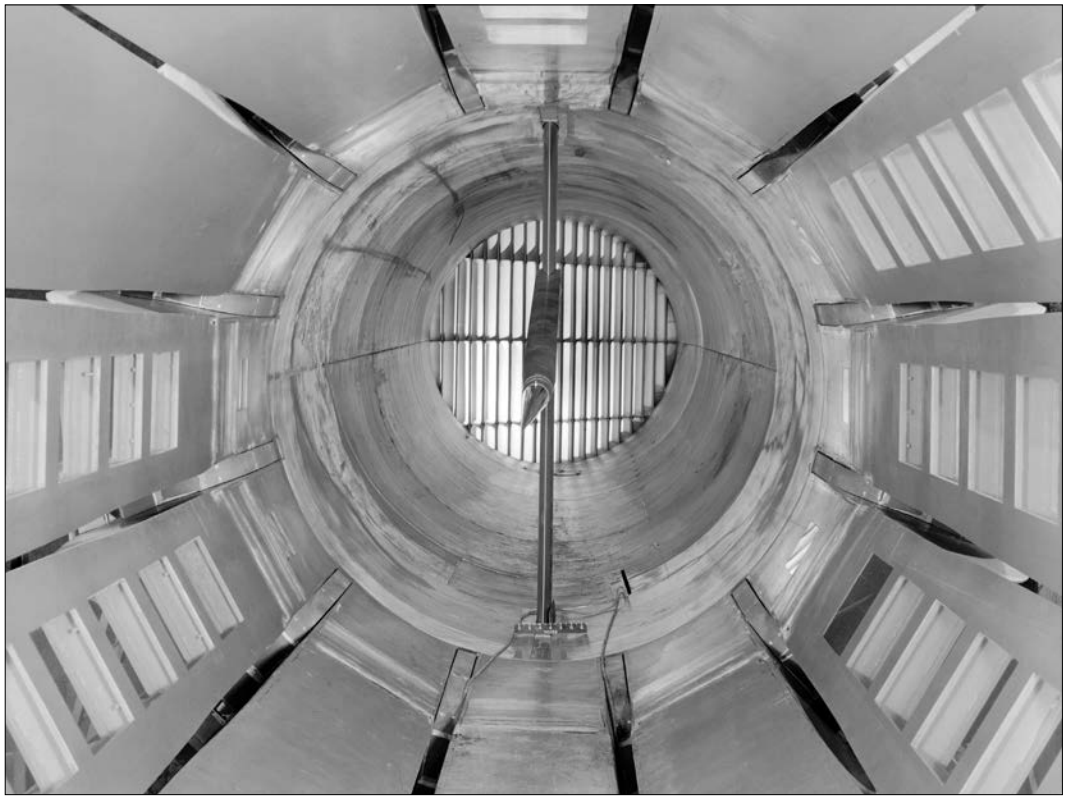
These 1951 section drawings illustrate the 8-Foot High-Speed Tunnel's configuration after the installation of the slotted wall test section. Unlike the original tunnel, the new test section was fabricated of steel. (Image credit: NASA LRC-1951-B701_P-71020)



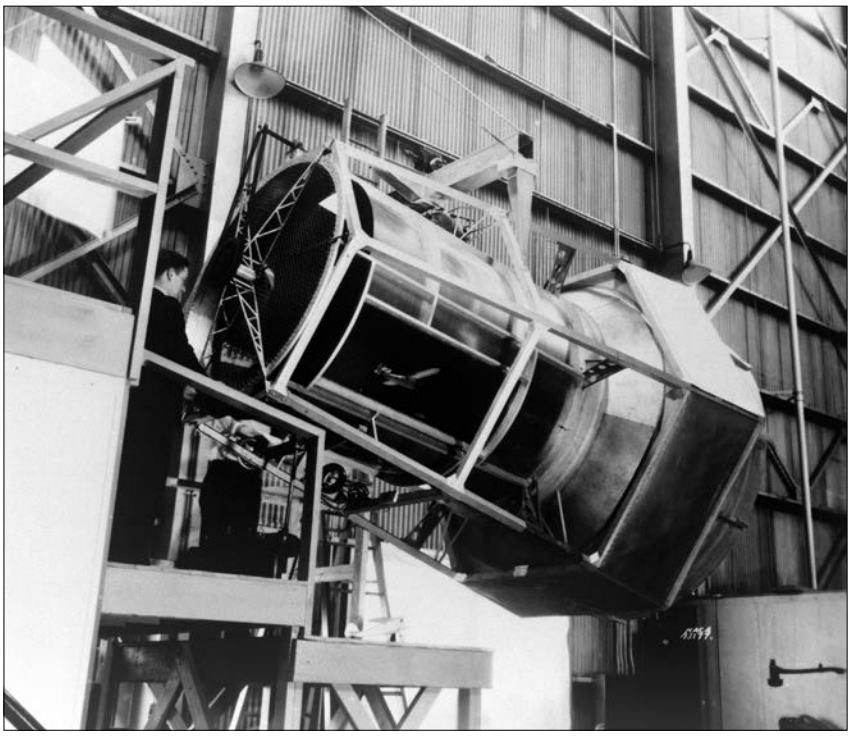
The 8-Foot High-Speed Tunnel shortly after its completion in 1936. The air-exchange tower and "igloo" surrounding the test section are clearly visible. (Photo credit: NASA LRC-1936-B701_P-12470)

This semiautomatic data-collection system was added to the 8-Foot High-Speed Tunnel in 1953. Though not a full-fledged computer, it was one of the NACA's early electronic data management systems. (Photo credit: NASA LRC-1953-B701_P-82293)

The differences between the original closed wall in 1936 (top) and slotted-wall (bottom) test sections in 1957 of the 8-Foot High-Speed Tunnel are readily apparent in these views. Note the curved reentry baffle at the end of each slot and the turning vanes in the background. The turning vanes were original equipment. (Photo credits: NASA LRC-1936-B701_P-11851 and NASA LRC-1957-B701_P-00959)



5-FOOT FREE-FLIGHT TUNNEL



The 5-Foot Free-Flight Tunnel in operation in 1937 with designer Charles Zimmerman acting as the model's pilot. Only the legs of the tunnel operator, standing behind the tunnel, are visible. (Photo credit: NASA LRC-1937-B701_P-13177)

SIGNIFICANCE

The 5-Foot Free-Flight Tunnel (5-Foot FFT) was built specifically to study the spinning and stability characteristics of airplanes by using pilot-controlled models in free flight. This novel facility was the first to have a complete wind tunnel movable in pitch and yaw so that it could follow the motions of a free-flying model. One researcher acted as a "pilot" to fly the plane while a second researcher controlled the tilt of the tunnel to keep the model centered in the airstream.

The 5-Foot FFT also represented an early use of automatic controls at Langley. The Instrument Research Division (IRD) developed a light-seeking device that made rapid minor corrections to the model's control surfaces to keep it aimed at a light placed at the tunnel's end. This apparatus virtually eliminated model crashes into the tunnel's walls, and the basic technology was later adapted for use by some guided missiles.

DESCRIPTION

The 5-Foot Free-Flight Tunnel was a self-contained machine erected in a portion of the test chamber of the Full-Scale Tunnel (Building 643) in Langley's East Area. The tunnel itself was fabricated primarily from steel channel and sheet metal, and the support and

pivot structure was steel, with wooden platforms for access and operation. It was an atmospheric, open-circuit tunnel.

The 5-Foot FFT had an exterior structure consisting of four hexagonal frames. These supported circular rings to which the tunnel walls were attached. The two inlet frames held a honeycomb flow straightener, which was followed by an entrance cone that reduced the cross section to 5 feet in diameter. For the remainder of the tunnel's approximately 12 feet, the diameter gradually increased. A 2-blade propeller, belt driven by a 5-horsepower, variable-speed electric motor, delivered a maximum speed of 25 feet per second through the tunnel. The propeller was mounted on a trussed, X-shaped frame at the outlet. A chicken-wire screen was placed immediately ahead of the propeller to catch an out-of-control model before it could hit the propeller or be ejected from the tunnel.[68]

The test section of the 5-Foot FFT had two lights to illuminate the interior in its top panel and two windows along the lower portion of its sides. These features allowed photographs and movies to be made of tests for later analysis.

In operation, the tunnel would be tilted so that its airflow angled up at an angle manipulated by an operator, who stood beside the tunnel. This air supported the model airplane, which would ideally remain centered and stationary in the tunnel. A second operator "flew" the model like a pilot while the first adjusted the tilt, horizontal slew, and speed of the tunnel to follow the model's response to control surface inputs. The concept worked, but actual operation proved to be challenging, as the model could easily diverge faster than an operator could follow it with the tunnel. This problem was most severe for yaw and combined roll-and-yaw maneuvers, and crashes into the tunnel's walls were common.

To deal with this problem, Langley's IRD developed an automatic control system that used a light-sensing device in the nose of the model to track a light placed at the end of the tunnel. Any reduction in the light sensed cause the system to initiate control surface adjustments on the model that re-aimed it at the light. Responding faster than the operator could, this system drastically reduced the crashes resulting from unplanned perturbations in the airstream.[69]

Models for use in the 5-Foot FFT were unlike most other wind tunnel models in that their weight needed to be scaled as accurately as their dimensions to fly properly. These lightweight models were built in the model shop set up specifically to build similar models for the spin tunnels.

HISTORY

Not all of the problems addressed by the NACA involved airplane design for speed and efficiency. Safety and controllability in flight were equally important, but these characteristics could not be evaluated with a model hard-mounted to a balance in a wind tunnel. But flight testing was dangerous and expensive, and the reason for a failure often disappeared with the pilot. To be useful, a model needed to be able to dynamically react to perturbations and control inputs without outside restrictions, so that the engineers

could evaluate its response. In 1936 Charles H. Zimmerman, the Langley engineer who had developed the center's vertical spin tunnels, suggested that an entirely new type of wind tunnel be built to investigate behavior in level flight.

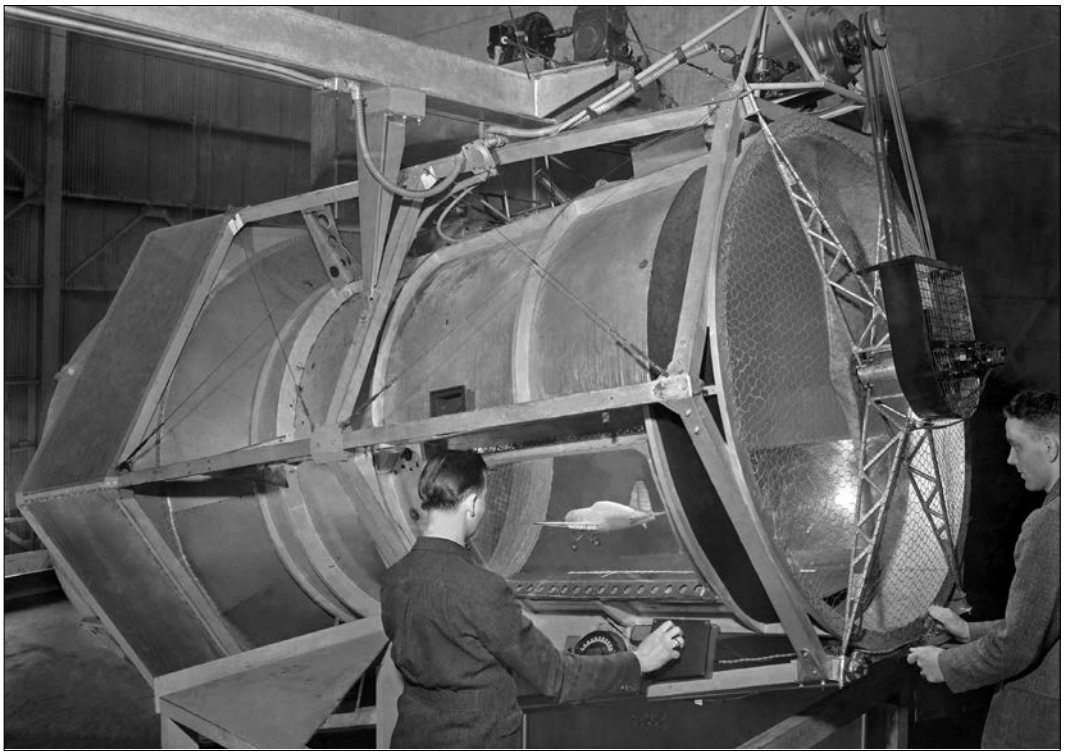
Zimmerman proposed a small, low-speed tunnel mounted on pivots so it could be tilted on a vertical plane and rotated on a horizontal one. Air flowing up through the tilted tunnel would just support the model when the tilt angle matched the plane's glide slope. This would approximate level flight, and once the model had been stabilized in the center of the tunnel, the test engineer "pilot" could "fly" it via electrical signals passed to the model over thin, flexible wires that trailed behind. Stationed just outside the tunnel and behind the model, the pilot was more or less oriented the way he would be in the model plane's cockpit. As he maneuvered the plane, a second operator could move the tunnel about its two axes as needed to keep it aligned with the model. Zimmerman's idea was quickly approved, and he began building the small, self-contained machine in a corner of the Full-Scale Tunnel's massive test chamber in 1936.

The 5-Foot FFT entered service in April 1937, and it quickly validated Zimmerman's basic concept, but flying a model plane in the tunnel proved to be more challenging than expected. The earliest tests involved nothing more than trying to keep the model stationary and level in the rising airstream, but even small perturbations could rapidly go out of control. Crashes into the tunnel walls were common, often destroying the lightweight models.

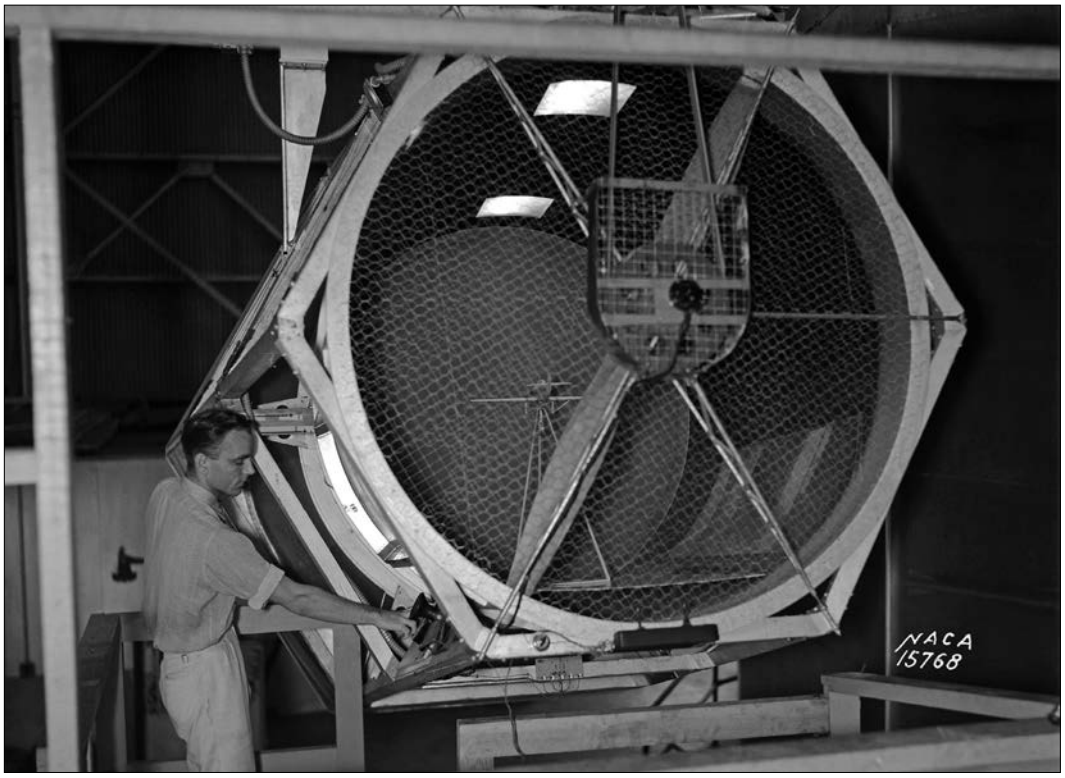
In an attempt to reduce these crashes, Zimmerman asked Langley's IRD for help. The IRD, under E. C. Buckley, built a relatively simple automatic control system that tracked a light placed at the end of the tunnel. A sensor in the model's nose looked for the light, and the system continually adjusted the control surfaces just enough to keep the model pointed at the light and, thus, aligned with the tunnel's centerline. The IRD's system worked well and sharply reduced the number of crashes. It also reduced the workload on the pilot, allowing him to concentrate on the test protocol more than on model survival.

Like other pioneering wind tunnels, the 5-Foot FFT served primarily as a prototype for a subsequent tunnel that would embody everything learned from the initial effort. It proved that the tilting-tunnel, free-flight technique was both practical and useful in controllability research, and it led to the development of an automatic, light-seeking control system whose basic concepts are still employed in some missile guidance systems. In operation, the 5-Foot FFT demonstrated that two-person operation was feasible, and that the next free-flight tunnel could benefit from an enclosure. The 12-Foot Free-Flight Tunnel, which was approved in 1937, incorporated all of these lessons.

Intended as a prototype to validate the design concept, the 5-Foot FFT was demolished sometime after the 12-Foot Free-Flight Tunnel entered service in 1939. No portion of it is known to have survived.

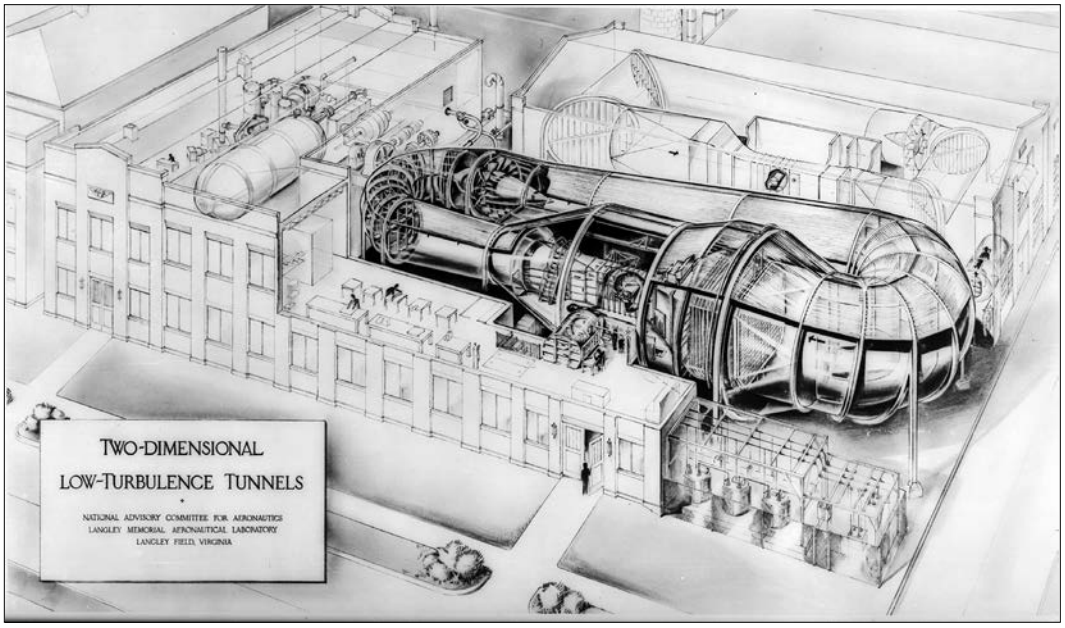


Two researchers were needed to operate the 5-Foot Free Flight Tunnel, seen here in 1939: one to fly the model airplane (R); and another to control the tilt, slew, and speed of the tunnel (L). (Photo credit: NASA LRC-1939-B701_P-17256)



This 1938 view of the 5-Foot Free-Flight Tunnel's outlet shows its hexagonal frame, belt-driven propeller, and outlet screen to catch errant models. (Photo credit: NASA LRC-1938-B701_P-15768)

TWO-DIMENSIONAL LOW-TURBULENCE TUNNEL (ICING TUNNEL)



Cutaway rendering of the Low-Turbulence Tunnel from 1946. (Image credit: NASA LRC-1946-B701P-49446)

SIGNIFICANCE

Completed in 1938, the Two-Dimensional Low-Turbulence Tunnel (LTT) was the NACA's first wind tunnel to use a very high contraction ratio of the entrance cone to smooth the flow of air through its test section. It also employed multiple screens ahead of the contraction as an additional turbulence-reducing measure. The LTT was built as an experiment to see if combining these two design elements would significantly reduce turbulence, which they did.

The LTT was also a monument to the resourcefulness of NACA engineers and managers in solving political as well as technical problems. Realizing that Congress was unlikely to understand the esoteric nature of turbulence, the NACA proposed it as an "icing tunnel" for the investigation of a serious and well-understood hazard. Though limited to a brief test series of ice formation and one means of de-icing, the LTT hosted the NACA's first ground-based icing study in 1938. Following that initial test, the tunnel was converted to serve its intended function of evaluating the merits of low-turbulence testing. By successfully demonstrating the effectiveness of these turbulence-reducing measures, the LTT became the prototype for the Two-Dimensional Low-Turbulence Pressure Tunnel.

DESCRIPTION

The LTT was a self-contained machine erected inside Building 188 (now 583) just northeast of the 24-Inch High-Speed Tunnel. Intended as a prototype for a permanent tunnel, it was constructed primarily of wood with exterior framing, although it was lined with sheet metal to provide as smooth an interior surface as possible. The tunnel measured 94 feet in length with a maximum width of 44 feet. The LTT's settling chamber, the portion of the tunnel having the largest cross-sectional area, was located immediately ahead of the entrance cone to the 7.5- by 3-foot test section. The settling chamber measured 21 feet square, and it contained a honeycomb flow straightener composed of 9-inch-square cells. A 30-mesh wire screen was attached to the upstream side of the honeycomb, and its downstream side was covered with a 60-mesh wire screen. In 1940, an additional set of seven 30-mesh screens was installed approximately 2 feet farther downstream. The honeycomb and screens were well-known devices to remove turbulent eddies from low-velocity airstreams.[70]

The LTT's most prominent feature was its radical entrance cone, which reduced the tunnel's cross-sectional area from 441 square feet in the settling chamber to only 22.5 square feet in the test section, a contraction ratio of 19.6 to 1. This was more than twice as high as any other NACA tunnel, and the reduction was accomplished in only 15 feet of length. The maximum air speed correspondingly increased from 8 to 155 miles per hour, though the tunnel could be run at slower speeds.

The LTT was a closed-circuit tunnel that used mitered corners with turning vanes. Its single propeller was located in the long return leg, just after the second corner. It was turned by a 200-horsepower DC electric motor housed in a streamlined nacelle. The motor's speed controls were located adjacent to the test section.

The tunnel was designed to test model airfoils that spanned the test section's 3-foot width. The test section walls had adjustable slots to allow the turbulent boundary layer of air along the walls to escape. The LTT's designers also installed a powered system to help control boundary-layer turbulence. A 45-horsepower blower extracted the boundary layer air through slots in the side walls about 8 feet downstream from the test section. A duct system passed this air to a second pair of vertical slots that smoothly re-introduced it to the tunnel. This system also had a small blower that added outside air. This provided the air needed to slightly pressurize the tunnel so that the test section slots could function. This boundary-layer control system was housed in a wooden box that surrounded the primary diffuser section of the tunnel.

HISTORY

Max Munk and Eastman Jacobs had put the NACA and Langley at the forefront of aeronautical research with their airfoil studies in the Variable-Density Tunnel (VDT) during the 1920s, and Jacobs had continued this work after Munk's departure. Pressurization to produce high Reynolds numbers was very successful, but Jacobs became increasingly concerned that the VDT's notoriously high level of turbulence affected the test results,

especially with regard to drag. Accordingly, in the mid-1930s, he began to lobby for a new pressure tunnel that would also have a more-laminar airstream. He ran into opposition from Smith DeFrance, head of the Full-Scale Tunnel group, and Theodore Theodorsen, who led the Physical Research Division, Langley's strongest theoretical group. DeFrance thought the FST gave better results than a new VDT would, and Theodorsen believed that theoretical analysis had surpassed empirical methods in most ways.[71]

Jacobs represented the NACA at the Fifth Volta Conference on High-Speed Aeronautics late in 1935, and he returned with considerable support for research into the detrimental effects of turbulence and how laminar flow around an airplane or airfoil could be promoted. Bolstered by this independent support, Jacobs finally managed to get Director of Research George Lewis's backing, but Lewis realized that Congress was unlikely to understand the esoteric nature of turbulence and boundary layer research enough to fund the effort. So Lewis did something of an end run and proposed an "icing tunnel" (also called a "refrigerated tunnel") to Congress. Ice had become a serious problem and caused several crashes, and Congress readily approved funds for the Icing Tunnel in 1937.[72]

The NACA was already doing icing research using airplanes in flight with some success, but a ground-based facility for such research appeared to offer numerous advantages in cost and safety. To evaluate the practicality of such research, Langley engineers built a 6-inch pilot tunnel with a brine cooling system, but the water cloud produced by the rudimentary spray nozzle and the ice accretion in no way resembled actual experience, and the experiment was soon abandoned. (In 1937, no one realized how difficult it would be to build an icing tunnel that would truly replicate in-flight conditions. That would finally be achieved some 10 years later in the Icing Research Tunnel at Cleveland.) Lewis, however, thought that one tunnel could be designed that could do some icing studies and at least begin to investigate ways to reduce turbulence.

Two approaches seemed to offer significant reductions in turbulence through the test section. Honeycomb flow straighteners had long been used, and they could be augmented with fine-mesh fabric screens to filter out turbulent eddies small enough to pass through a honeycomb. A more radical concept involved using an entrance cone with a very large contraction. This would allow the slowest possible air speed in the settling chamber, which was also where the screens would be, followed by a rapid acceleration to test-section speed. Jacobs and Ira Abbott, another Langley engineer who assisted Jacobs on the design, believed this rapid change would delay the formation of eddies along the test section walls. Taking the concept almost to the extreme, they designed the entrance cone with a 19.6-to-1 contraction ratio. To further enhance laminar flow, they added adjustable vertical slots in the test section wall and a system of wall scoops downstream with a 45-horsepower blower to extract the boundary layer of air along the walls and re-inject it into the tunnel in smooth sheets farther downstream. A second, smaller blower augmented this recirculating air with outside air, giving the tunnel a

slightly positive static pressure. This excess air bled off through the test section slots, taking turbulent eddies with it.

The LTT was, without question, an experiment in wind tunnel design at least as much as it was an experiment in either icing or turbulence-free research. For simplicity and minimum cost, it would not be pressurized, and it would be a so-called "two-dimensional" tunnel. This term refers to a wind tunnel with a vertical-to-horizontal, or vice versa, ratio large enough that air flows in one spatial direction can be neglected, making analysis of pressures and flows in the other two directions—vertical and chord-wise in this case—easier. In practice, two-dimensional tunnels are most useful with full-span models, such as airfoils, which were exactly what Jacobs intended to test. To further reduce its cost, the LTT would be made of wood with a thin, sheet metal liner.

The LTT was never intended to be a high-speed tunnel, and its maximum speed was about 155 miles per hour. It used a single fan driven by a 200-horsepower DC motor. This yielded a maximum dynamic pressure of 60 pounds per square foot and a Reynolds number of 1.4×10^6 per foot of model chord. Neither range was high, but the LTT's mission was to streamline airflow. Essentially, it would be the pilot tunnel for a pressurized tunnel that would increase Reynolds number and dynamic pressure to the desired levels.

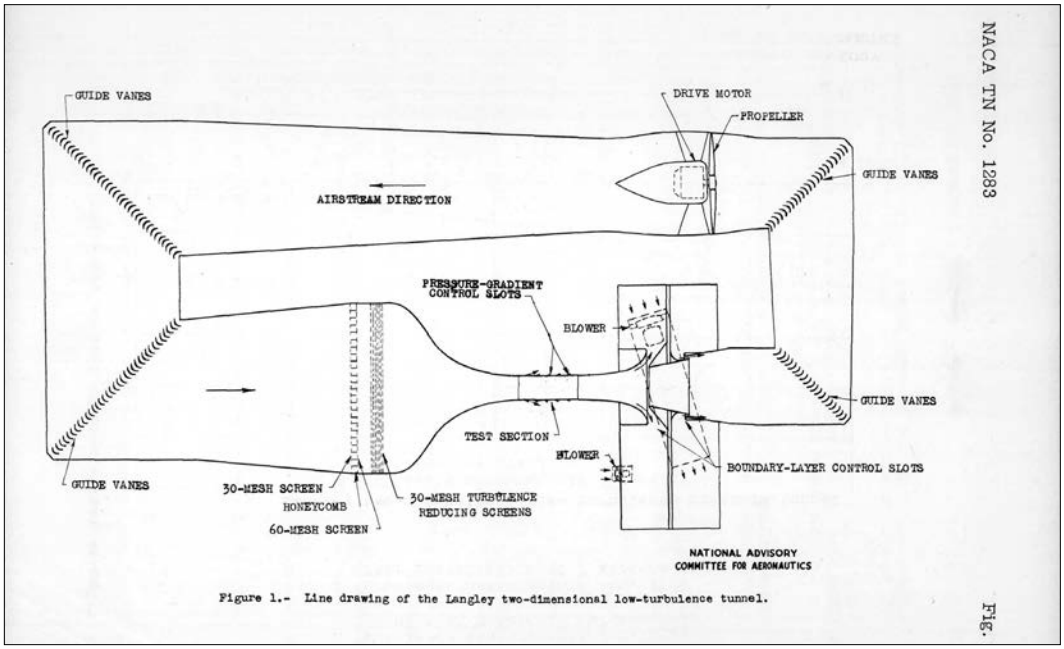
To accomplish its icing mission, the designers insulated the LTT with kapok cut from surplus navy life jackets, and they included a crude refrigeration system using dry ice to chill a large tank of ethylene glycol. Shortly after the tunnel had been completed and checked out in June 1938, the operators charged the refrigeration system with dry ice and started the glycol pump. The cold glycol flowed through coils that cooled air drawn from and returned to the tunnel. Even though these coils dehumidified the air in the tunnel somewhat as it cooled, some ice formed on the leading edge of an airfoil. A short series of tests using hot air to simulate engine exhaust circulated through the airfoil followed. The icing tests were quickly proclaimed a success, and the refrigeration equipment and insulation were removed to enable the LTT to begin its real mission of turbulence-reduction studies.[73]

The LTT validated its designers' concepts, reducing test section turbulence to unprecedentedly low levels. Turbulence was determined by measuring the variations in static and dynamic pressures at various angles throughout the test section airstream. Flows at angles other than straight through indicated turbulence. Where the VDT, having a 4-to-1 contraction ratio, exhibited variations of around 2 percent, and the 8-Foot High-Speed Tunnel with its 9-to-1 ratio had about 0.5 percent, the LTT brought the turbulence down to less than 0.2 percent. Early tests of a low-drag airfoil produced drag coefficients about half of those generated in the VDT, and these results were validated by in-flight tests. Further analysis indicated that the flow was laminar over more than half of the airfoil's chord. (Jacobs had already started to think about the relationship between laminar and turbulent flows and drag, and these results urged him toward additional investigations that would ultimately lead to the NACA's 6-series of "laminar-flow" airfoils.)[74]

The success of the LTT's radical contraction ratio spurred a rapid application for funds to construct a permanent, pressurized version that could enable a greater range of testing under low-turbulence conditions, and Congress authorized the Two-Dimensional Low-Turbulence Pressure Tunnel (LTPT) at Langley within a few months of the LTT's opening. Research continued in the LTT until the LTPT's completion in 1941, but it declined rapidly afterward. Nevertheless, the LTT continued in service throughout World War II. The speeds of the jet age rendered it obsolete after the war, and the tunnel was dismantled during 1947–48. No part of it is known to have survived.

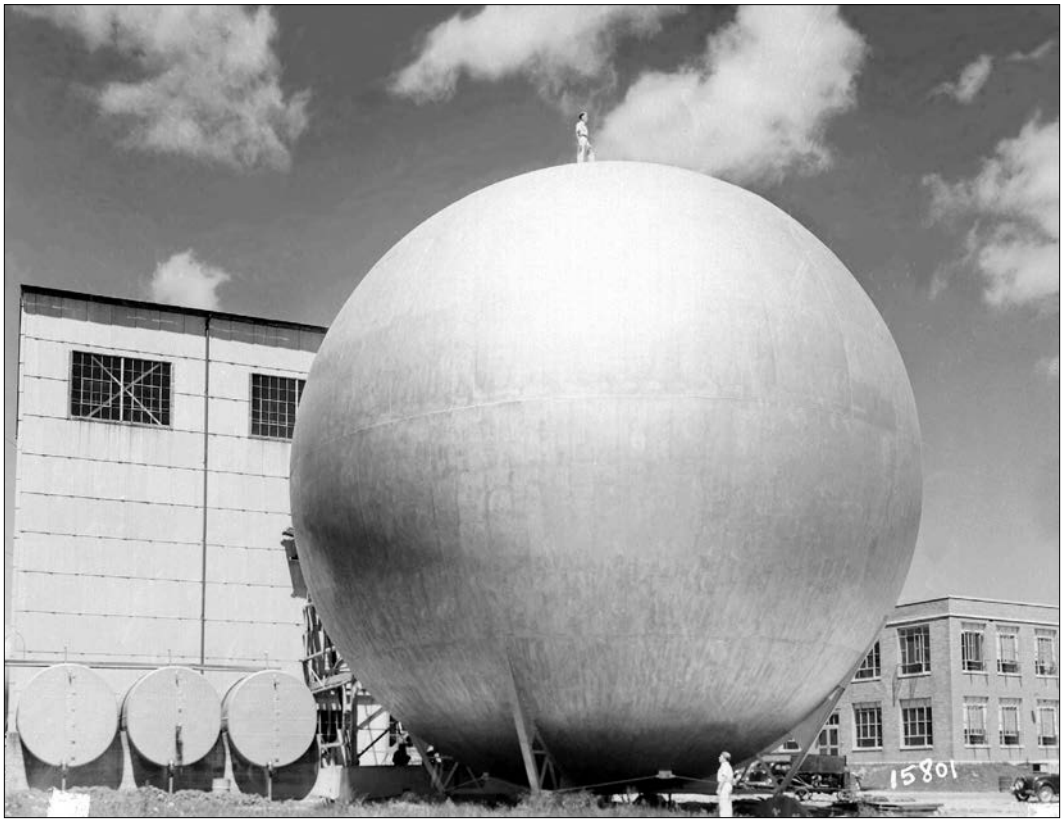
Erection of the "Refrigerated Tunnel" was in its early stages when this photo was taken in 1938. Note the wooden construction. (Photo credit: NASA LRC-1938-B701_P_F001-14845)

The unusual proportions of the Low-Turbulence Tunnel's test section are evident in this 1939 view looking upstream from the diffuser (left). A technician is making adjustments to a rake of pressure probes at the trailing edge of an airfoil. The enlarged view (right) shows the airfoil and pressure rake set for a test. This arrangement was used for determining the thickness of the turbulent boundary layer along an airfoil's trailing edge. (Photo credits: NASA LRC-1939-B701_P-17184 and NASA LRC-1939-B701_P-17181)



This plan drawing of the Low-Turbulence Tunnel shows the several screens and the 19.6-to-1 contraction just ahead of the 7.5- by 3-foot test section, as well as the ducts and blowers for boundary-layer control along the tunnel's sidewalls. Built as the Icing Tunnel, it hosted only a short series of icing tests before being renamed the LTT and beginning to do the low-turbulence testing its builders actually intended. The equipment for the original icing tests is not shown. (Image credit: NACA TN-1283, Fig. 1)

12-FOOT FREE-FLIGHT TUNNEL
12-FOOT LOW-SPEED TUNNEL



External view of the 12-Foot Free-Flight Tunnel as it neared completion in 1939. Building 646 is at left, and the two workmen standing on and under the sphere furnish a sense of scale. (Photo credit: NASA LRC-1938-B701_P-15801)

SIGNIFICANCE

The 12-Foot Free-Flight Tunnel (12-Foot FFT) was the NACA's second tilting wind tunnel built specifically to study the controllability of airplanes in free flight. It was converted into a non-tilting tunnel and renamed the 12-Foot Low-Speed Tunnel (12-Foot LST) in 1968, and this conversion represents an efficient, inexpensive conversion from a highly specialized wind tunnel to one suitable for a variety of preliminary aerodynamic investigations at low cost.

DESCRIPTION

When built, the 12-Foot FFT had an appearance unlike that of any other tunnel, and the external appearance remains unchanged as the 12-Foot LST. One can still see a 60-foot-diameter steel sphere, Building 644, attached to a three-story service structure, Building 646. For the 12-Foot FFT, the merits of this sphere were only apparent once inside it. Balanced on top of a large A-frame structure was a relatively compact wind

tunnel with a 12-foot octagonal test section, 15 feet in length. Its inlet vanes and settling chamber hugged, but did not touch, the inside of the sphere. Downstream from the test section, a six-blade wooden propeller discharged air into the sphere, which functioned as an annular return duct. As with the Five-Foot Free-Flight Tunnel (5-Foot FFT), this one could pivot on the A-frame's trunnions to change pitch, actuated by a hydraulic jack. Since what looked like an open-circuit tunnel could pivot freely inside the sphere, it actually functioned as a closed-circuit tunnel with the same configuration, regardless of its pitch angle. The pitch angle ranged from 40 degrees above horizontal to 15 degrees below.[75]

To accommodate larger, heavier models than its predecessor, the 12-Foot FFT had a 600-horsepower, DC motor turning a wooden, six-bladed fan that measured 15 feet, 10 inches in diameter. The combination provided a maximum speed of 90 feet per second (61 miles per hour).[76]

The operational concept was the same as for its 5-Foot FFT predecessor, except for the location of the tunnel operator and pilot. Instead of standing on a fixed platform, both rode the tunnel itself, the tunnel operator at one side near the trunnion, and the pilot in a seat just below and behind the test section, looking through a canopy-like bubble in the floor. The tunnel operator viewed the test through large windows. As with the 5-Foot FFT, the tunnel operator used speed and tilt controls to keep the flying model centered in the test section. Three motion-picture cameras located above, behind, and alongside the model recorded the tests.

Though built for free-flight testing, the 12-Foot FFT was fitted with a six-component balance for force-and-moment testing by 1943. This addition allowed qualitative free-flight test observations to be correlated with quantitative data under the same test conditions.[77]

Converted to the 12-Foot LST in 1968, the tunnel looks much the same as it did as the 12-Foot FFT, but there are significant differences. The tilt mechanism and A-frame support were removed, and the tunnel was fixed in a horizontal position within a new steel frame. With tilting no longer employed, the pilot and tunnel operator control stations were removed. A sting mount on a movable C-strut became the primary model mount, and the addition of a strain-gage-type balance and electronic data acquisition and control hardware allowed all of the tunnel's control functions to move into a new control room built on the third floor of Building 646. Numerous rigid electrical and piping connections have since been made to the tunnel, since the flexibility needed for tilting is no longer required. The current specifications for the 12-Foot LST show its motor rated at 280 horsepower and its maximum speed as 77 feet per second (52.5 miles per hour). This will produce a dynamic pressure of 7 pounds per square foot and a Reynolds number of 492,000 per foot.[78]

HISTORY

While much of what the NACA researched involved airplane design elements for speed and efficiency, safety and controllability in flight were equally important, but control-response characteristics could not be thoroughly evaluated with a model hard-mounted to a balance in a conventional wind tunnel. With flight testing dangerous and expensive, Langley engineer Charles Zimmerman devised several specialized wind tunnels to tackle the problems. One was a prototype tilting tunnel that could be adjusted to match an airplane's glide angle, allowing the model to glide freely in the airstream and respond to control inputs as the real aircraft would. Zimmerman proved the concept to be practical and useful with his prototype 5-Foot Free-Flight Tunnel (5-Foot FFT). With its success, he sought the funds to build a larger, permanent version, and the 12-Foot Free-Flight Tunnel was approved in 1937.

The 12-Foot FFT, also designed by Zimmerman, improved significantly on its predecessor. Because of his awareness of the improvements in test consistency that a closed-circuit design could provide, this became one of his design goals, but arranging a conventional closed-circuit design to tilt did not seem practical. In an ingenious move, Zimmerman designed what is probably the most unusual-looking wind tunnel ever built. He placed the tunnel on trunnions at the top of an A-frame structure inside a 60-foot-diameter steel sphere. He did not use a sphere to put the 12-Foot FFT under pressure, as the shape and "air lock" callouts on some drawings might imply. This was to be an atmospheric tunnel. The sphere was used because it would respond to thermal changes more uniformly than other shapes and because it would not present sharp corners to the return air flow.

With the new tunnel more than twice the size of its predecessor, Zimmerman changed to an octagonal cross section with 12 feet across its flats in the test section, which he made 15 feet long. The entrance cone featured a short contraction preceded by a honeycomb flow straightener. Ahead of the honeycomb were radial inlet vanes whose ends were contoured to match the curvature of the sphere, but not contact it.

As in the 5-Foot FFT, Zimmerman specified induced draft, and he placed a 15-foot, 10-inch–diameter fan in a circular exit cone 5 feet from the end of the test section. This fan had six blades and was powered by a 600-horsepower, variable-speed DC motor. A screen just ahead of it would catch any out-of-control models before impact.

To give the pilot a view as close to what he would see sitting in a real airplane, Zimmerman placed his "cockpit" below and behind the test section. The pilot's head protruded into the air stream, protected by a teardrop fairing. From this location, he faced into the wind like the model, and he could clearly see every movement it made, especially its behavior in yaw and roll. The tunnel operator, who Zimmerman placed just outside the tunnel to the model's left, managed all other aspects of the test. He controlled the model's propeller speed, the tunnel's air speed, and the tunnel's tilt. In essence, he was responsible for keeping the model flying in the central region of the

tunnel while the pilot made various maneuvers to evaluate its response to control inputs. Electromagnetic actuators moved the model's control surfaces. A thin electrical cable trailing behind the model from its center of mass to the pilot's station carried motor power and control signals to the model while having very little effect on the test.[79]

The free-flying models were quite different from the statically mounted models employed in most wind tunnels. They were, to use Shorter and Osterhout's term, "dynamic scale models." In much the same way that fluid parameters were changed to match the Reynolds number and achieve *fluid* similitude, certain physical changes were needed in the model to achieve *solid* similitude, since the dynamic response of the solid model was of primary importance here. As with models for the spin tunnels, these models had to have mass distributions scaled in a specific manner to make them replicate the dynamics of their full-scale prototypes. A special model shop—one separate from the conventional model shop—built models for both the spin and free-flight tunnels. Wingspans were limited to about 40 inches, so most models were approximately 1/10 to 1/12 scale.[80]

The 12-Foot FFT entered service in 1939 (shortly after Zimmerman left Langley), and the research team soon established a test routine. Model flight tests began with a takeoff that mimicked a full-sized one. With the model resting on its landing gear, the operator simultaneously increased the speeds of the model and tunnel's propellers. The model's tail soon rose, and at the right moment, a slight elevator movement from the pilot caused it to lift off the floor. The tunnel operator then brought the speed and tilt up to test condition with the model centered in the tunnel. At that point, the pilot could begin the planned series of maneuvers, depending on the tunnel operator to adjust the tunnel's speed and angle of tilt accordingly. Gliding flights depended on the tilt of the tunnel matching the model's glide slope, but powered flights often began with the tunnel horizontal and covered a wide range of tilt. Zimmerman had designed the tunnel to accommodate glide angles from a 40-degree dive to a 15-degree climb.[81]

These dynamic tests generated considerable qualitative information about airplane handling, and they often demonstrated the worth, or lack of it, of design changes like increasing the dihedral angle of the wing or adding a dorsal fin ahead of the tail. But correlating the pilot's observations with quantitative data, the actual forces and moments involved in some maneuver, required a static test with a model mounted on a balance. Joseph Shortal designed a six-component balance that could be mounted on top of the 12-Foot FFT with the model suspended from it in an inverted position. The top-mounted design did not interfere with the A-frame, and it allowed the same models to be tested statically on the balance and dynamically in free flight. The control surfaces were preset during static tests, making it possible to duplicate specific free-flight conditions. Other tests used only the balance mode, particularly when investigating unusual handling characteristics found in full-sized airplanes.[82]

The 12-Foot FFT proved most useful in investigating the handling characteristics of new and unconventional designs, particularly new jet designs after World War II.

It remained in active service into the 1950s, yielding this task only after the Full-Scale Tunnel acquired equipment that enabled free-flight testing of larger, more sophisticated models. But the 12-Foot FFT was not ready for the boneyard just yet.

Aerospace engineers continued to need simple, exploratory wind tunnels where they could test basic new ideas for aircraft and components inexpensively before they committed large resources on an extensive test program in more-sophisticated tunnels. This need still exists, albeit less frequently, today, where computational fluid dynamics software can still lack the ability to correctly analyze an unusual design. Since it already had a balance, the underutilized 12-Foot FFT became just such a facility, and engineers increasingly booked it for preliminary testing. By 1968, these needs had grown sufficient in number and variety to justify rebuilding the tunnel, and its engineering team reconfigured it into a fixed, horizontal tunnel for static testing. NASA renamed it the 12-Foot Low-Speed Tunnel.

To convert the tunnel for full-time static testing in an inexpensive manner, the engineers decided to retain the basic arrangement of a tunnel within a sphere, but they replaced the A-frame base and trunnions with a fixed structure that supported the tunnel on both ends. The tunnel's drive fan and motor, as well as its octagonal cross section, were also retained, although the inlet was reconfigured. A new floor-mounted balance with a C-shaped strut and sting replaced the overhead balance. This was made possible by the removal of the old A-frame, and it also allowed the adoption of modern, electronic instrumentation. The C-strut permitted very high angles of attack, ideal for investigating many complex, low-speed aerodynamic phenomena.

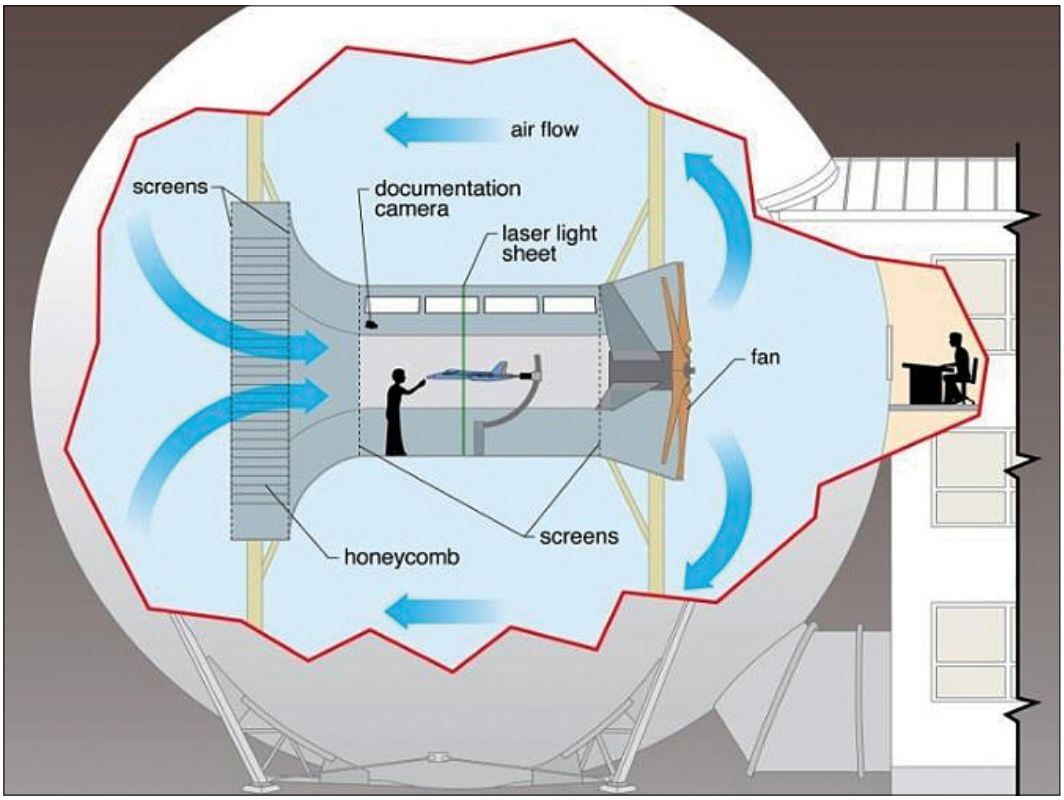
The fixed arrangement also allowed removal of the two tunnel-mounted control stations for operator and pilot. All controls were moved into a former observation room on the third floor of adjacent Building 646. With increasingly sophisticated instrumentation and control equipment, test routines became preprogrammed and automated, though test engineers could watch the results and alter the routines as needed. The tunnel's test capabilities and applications have expanded well beyond what Zimmerman and his colleagues ever imagined.

Today, the 12-Foot LST continues to see a wide variety of tests. It is capable of static testing, using sting-mounted models with internal, strain-gage balances; free-to-roll testing to investigate roll and wing rocking issues; dynamic pitch testing at high acceleration rates; and several types of flow-visualization studies. Flows are most commonly visualized using two methods: the classic method of observing hundreds of tufts applied to the model, which now uses fluorescent tufts and ultraviolet light; and the newer particle-imaging velocimetry (PIV) technique, where very fine propylene glycol smoke particles pass through a sheet of light projected by an overhead laser. The sheet of light can be directed around any part of the model, and it makes the smoke particles visible to recording cameras. Many of these images can be computer-combined to generate images of flows at all points around the model. Models can be powered, and techniques

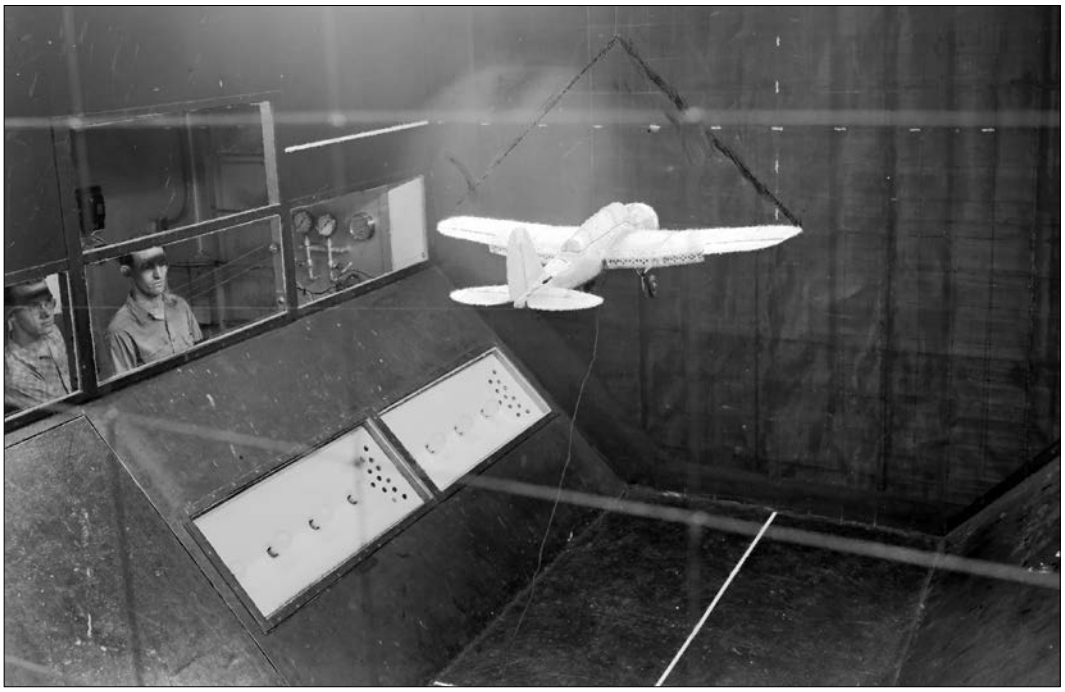
now being pioneered allow the same kind of dynamic testing now done in pitch to be performed in roll and yaw as well.[83]

In August 2022, Langley broke ground for a new wind tunnel, the Flight Dynamics Research Facility (FDRF), with superior capabilities at the site of the 12-Foot Low Speed Tunnel and the Vertical Spin Tunnel. The two older tunnels will be demolished upon completion of the new facility.

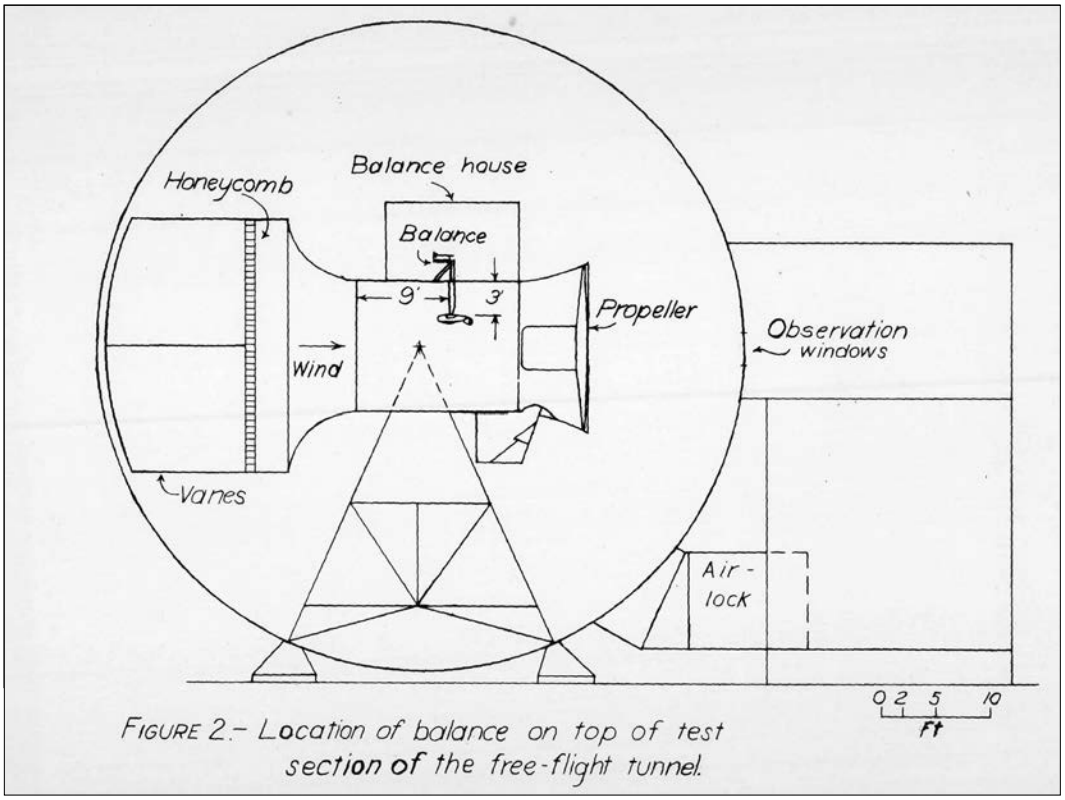
This advanced-concept model of a blended wing-body transport saw low-speed testing in the 12-Foot Low-Speed Tunnel during 2000. (Photo credit: NASA LRC-2000-B701_P-00548)



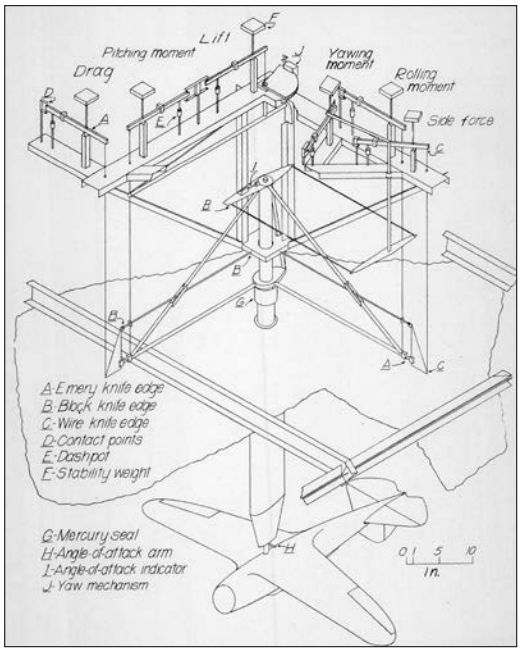
This cutaway drawing shows the current 12-Foot Low-Speed Tunnel configuration. Note the fixed support frame, C-strut with sting, and modified entrance cone. (Image credit: AIAA 2014-3000, Fig. 9)



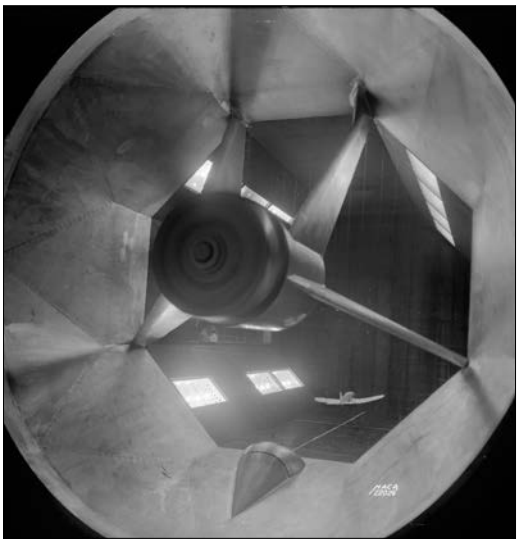
This view of the 12-Foot Free-Flight Tunnel's test section in 1940, with a $^{1}/_{12}$-scale model of SBN-1 under test, shows the pilot at the left with the tunnel operator and an observer behind the windows. The thin wire carrying electrical control signals from the pilot's station to the model can barely be seen. (Photo credit: NASA LRC-1940-B701_P-21002)



This drawing shows the general arrangement of the 12-Foot Free-Flight Tunnel and its major components. The tunnel itself pivoted about the top of the A-frame support. (Image credit: NACA ARR-3D17, Fig. 2)

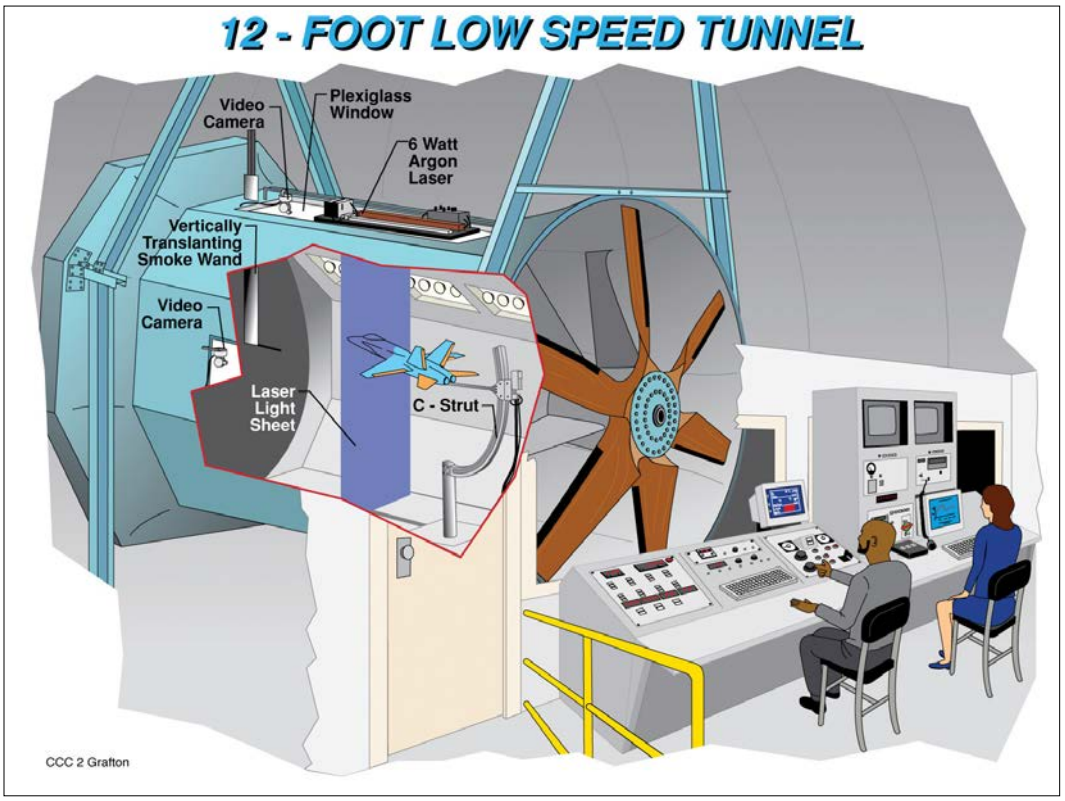


This diagram of the 12-Foot Free-Flight Tunnel's 6-component balance shows its major parts and how the models were hung in an inverted position. This arrangement avoided interference with the tunnel's A-frame support. The tunnel was set in its horizontal position for tests using the balance. (Image credit: NACA ARR-3D17, Fig. 3)



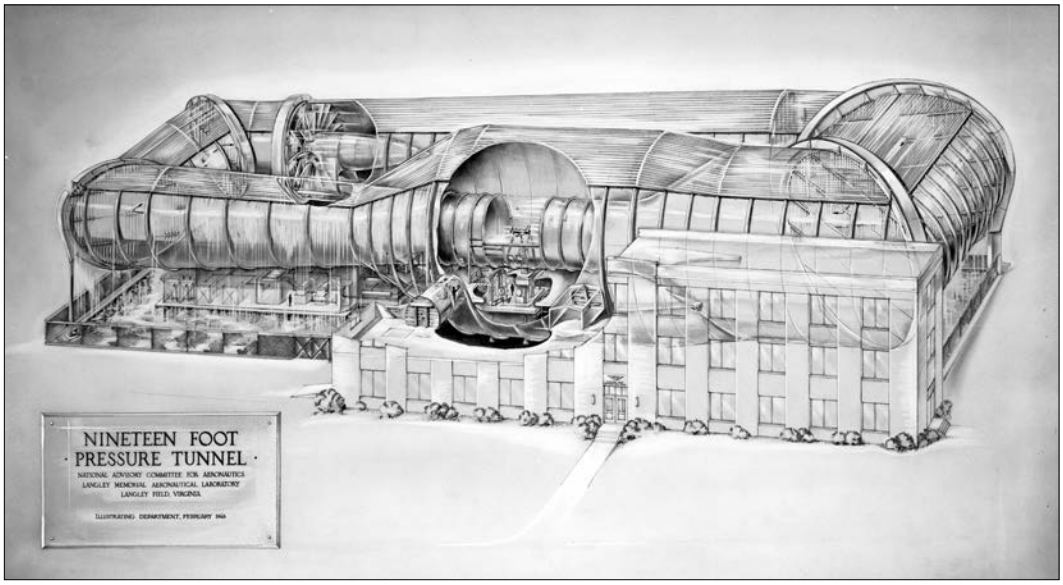
Looking through the 12-Foot Free-Flight Tunnel's spinning fan at a model XF4U-1 in 1940. The pilot is inside the teardrop protrusion at bottom, while the tunnel operator (out of view) controls the tilt and speed. (Photo credit: NASA LRC-1940-B701_P-22026)

A special model shop, seen here in 1939, built the lightweight flying models for the spin and free-flight tunnels. Balsa was the primary material used. (Photo credit: NASA LRC-1939-B701_P-18684)



This drawing shows an F/A-18 Hornet during a particle-imaging velocimetry (PIV) test in the 12-Foot Low-Speed Tunnel. Smoke particles are made visible when they intersect the laser sheet, providing a detailed picture of the flow field. (Image credit: NASA CCC 2 Grafton)

19-FOOT PRESSURE TUNNEL



This phantom drawing of the 19-Foot Pressure Tunnel shows its arrangement and size. Note the open test section, plenum, airlock, awning, and cooling water dripping from the tunnel. (Image credit: NASA LRC-1979-B701_P-07078)

SIGNIFICANCE

The 19-Foot Pressure Tunnel (19-Foot PT) was the NACA's first wind tunnel to be both very large and pressurized. As such, it combined the pressurization of the VDT with the large-scale capabilities of the PRT and FST to generate Reynolds numbers close to those of actual flight using relatively large models. It was also the NACA's first very large wind tunnel to be constructed entirely of steel with an integral support system, a design that would be employed on numerous subsequent tunnels.

DESCRIPTION

The 19-Foot PT was a large, closed-circuit wind tunnel with a circular cross section and four mitered corners. It occupied an entire block in the East Area, one block northwest of the FST. Designed to be pressurized, its heavy-gage, arc-welded steel shell was ringed with structural-steel hoops. The corner rings, as well as some others, were of heavier construction that transferred the weight of the tunnel to support legs, which rested on concrete foundations. A two-story brick building along the tunnel's northwest side housed model-preparation shops and office areas for the tunnel. An airlock provided access from the second floor to the tunnel's test chamber, which was contained within a 55-foot-diameter plenum that served as the test chamber's pressure vessel. This design minimized penetrations through the pressure shell to simplify its construction and improve its integrity.[84]

The 19-Foot PT had an open test section with a circular entrance cone similar to that in the 20-Foot PRT. It delivered a 19-foot-diameter jet of air across the test section. Models were supported in this airstream on a three-strut stand that rested on the six-component balance located directly below the test section, adjacent to the tunnel's control panel. As in other contemporary wind tunnels, the balance consisted of a system of levels that conveyed the forces from each of the three support legs to one or more industrial scales. These scales each contained a printer, all of which were activated simultaneously by a button on the control panel.

An exit cone with a flared inlet led directly to the tunnel's diffuser and first corner. The test chamber plenum tapered to join the tunnel shell ahead of the corner. This corner, like the other three, was fitted with airfoil-shaped turning vanes to minimize turbulence and energy loss through the 90-degree direction change. The second leg and second corner directed the air into the third leg. The tunnel's propeller fan was located in the third leg. From the fan, the air passed through the remainder of the third leg, the third corner, the fourth leg, and the fourth corner to reach the settling chamber and entrance cone. The test chamber plenum flared up to its maximum diameter after the fourth corner. Through the circuit, the tunnel's diameter steadily increased from approximately 20 feet at the exit cone to its maximum of 50 feet in the settling chamber.

The 19-Foot PT's 34.5-foot-diameter, 8-blade propeller was driven by an 8,000-horsepower, variable-speed DC motor enclosed within a streamlined nacelle. Surrounding the nacelle were countervanes—vanes pitched opposite the pitch of the fan blades to eliminate most of the swirl imparted to the air by the fan. A Ward-Leonard system provided continuously variable speed control up to the tunnel's maximum of 330 miles per hour.

The tunnel could handle pressures between near-zero and 40 psia (near-0 to 2.7 atmospheres), though the tunnel rarely operated under a vacuum. As with other pressurized wind tunnels, operating under positive pressure increased the Reynolds number to more closely simulate actual flight by a full-sized airplane. Model mounting and test preparation were done at ambient pressure, and the tunnel was pressurized only after these were complete. Once the tunnel was under pressure, engineers and technicians used the airlock for access to the test chamber to avoid delays for depressurization and repressurization. The airlock door could not be opened against a vacuum.

To minimize temperature changes during test runs, a corrugated-steel awning covered most of the tunnel to shield it from solar heat. For heat removal, a system of nozzles under the awning sprayed water on the tunnel's outer surface. Some of this water evaporated, but most dripped off the sides of the tunnel into a moat of crushed stone that covered the ground below the tunnel's circuit, carrying considerable heat with it.

HISTORY

While the VDT had put the NACA and Langley on the map of major aeronautical research agencies, it did have decided limitations, including a low (51 miles per hour)

speed and a high degree of turbulence due to its sharp return bends and short overall length. Eastman Jacobs began lobbying for a "Super VDT," in which he hoped to combine the pressurization of the VDT with the large size and cleaner flow of the FST. This, he believed, would solve any scale-effect problems and allow him to pursue his latest interest, boundary layer studies. Boundary layer studies had moved to the forefront of Langley's agenda, but Engineer-in-Charge Reid vetoed Jacobs's 1935 proposal after receiving negative comments on it from Theodore Theodorsen, Physical Research Division Head, and Smith DeFrance, head of the FST Section, both of whom believed such a tunnel would offer little, if any, new capability. Theodorsen favored a greater emphasis on theoretical aerodynamics, and DeFrance had aspirations for a new PRT that *his* group would manage. Though severely wounded for a time, Jacobs's idea did not die.

Both the VDT and the PRT had become outdated by 1935, and Reid, like DeFrance, had a "Super PRT" on his wish list for when funds became available. Ultimately, threatened by new aeronautical laboratory construction in Europe during the increasingly contentious 1930s,[85] these ideas would lead to not one, but four new wind tunnels at Langley before the United States found itself embroiled in World War II, as well as the construction of two new NACA laboratories at Sunnyvale, California, and Cleveland, Ohio.

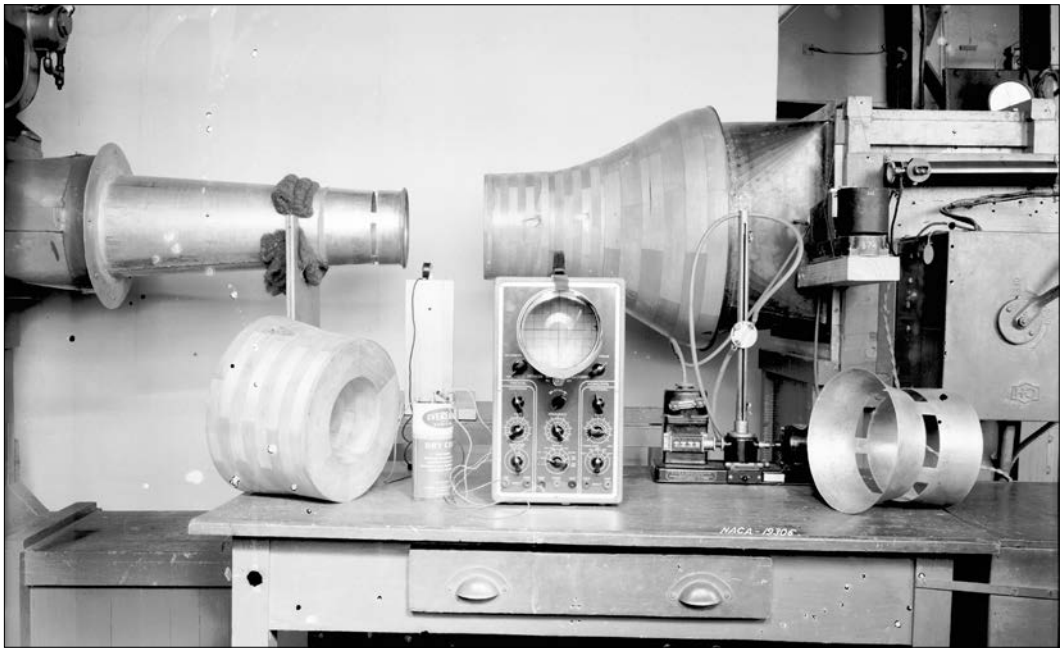
The PRT had proven the validity of full-scale propeller testing, but engine and propeller performance had gone far beyond conditions that the PRT could duplicate. Understanding propeller performance at airplane speeds above 300 miles per hour, with propeller-blade tip speeds approaching sonic velocity, looked to be a crucial element for the next generation of aircraft. As with many aerodynamic tests, achieving a sufficiently high Reynolds number (around 9 million per foot minimum) was essential. Pressurization would allow this at lower speeds and with a much smaller drive motor than if the tunnel operated at atmospheric pressure like the PRT, and consequently reduce the operating cost.

What emerged from these design tradeoffs in 1939 was the 19-Foot PT, the first wind tunnel to combine large size with high pressure. The design team, led by Smith DeFrance and John F. Parsons, a mechanical engineer who had come to Langley after graduation from Stanford nine years earlier, produced a tunnel with a 19-foot-diameter test section that was, along with its control and balance areas, enclosed in a large pressure vessel. It and the remaining walls of the tunnel were fabricated of heavy-gage steel and braced by a structure capable of withstanding both high vacuum and positive pressure inside the tunnel. The pressure vessel around the test section measured 55 feet in diameter, and operating personnel entered through an airlock/decompression chamber whose doors could not be opened when the tunnel was under high vacuum. Though larger, the 19-Foot PT borrowed heavily from the design of the Wright Brothers Wind Tunnel at MIT. That tunnel, opened in 1938, was the first tunnel to utilize an externally braced steel pressure shell with a plenum enclosing the test section and support areas.

As much of an improvement as the 19-Foot PT was over the PRT, it quickly became apparent—even before it went into service—that 330 miles per hour was still too slow

for truly high-speed propeller research. Having cost over $1,000,000 to build, it stood as a grand solution to an inadequately defined problem. Nonetheless, the 19-Foot PT, with large-scale models of complete airplanes at high Reynolds numbers, proved to be well-suited for stability, stall behavior, and lateral controllability investigations, and it performed a variety of practical tests. Aircraft studied included the F4U-1 fighter and proposed designs for the XA-26 and XTB2D-1, but perhaps its most interesting programs involved the first true strategic bomber, the B-36. The 19-Foot PT hosted some of the earliest tests of stall characteristics and aileron effectiveness of the prototype XB-36 in 1945, and a program 11 years later investigated the possibility of attaching two RF-84F reconnaissance fighters to the wingtips of a B-36J.[86] The primary concern for these tests was flutter, potentially destructive interactive oscillations involving the three airplanes. Other postwar tests involved the stability and stalling characteristics of jets during slow-speed flight, often with flaps extended.[87]

In spite of these practical tests, almost everyone at the NACA continued to regard this tunnel as an expensive disappointment, and it never lived down its reputation as something of a "white elephant." But the 19-Foot PT's basic configuration and modern, all-steel design made it amenable to modification. Thus, when aeroelasticity and flutter became an increasing concern in the 1950s, the 19-Foot PT, which had already hosted some flutter tests, became the core for a complex new tunnel, the Transonic Dynamics Tunnel (TDT), designed and built specifically to investigate this phenomenon.[88] The 19-Foot PT closed for the extensive modifications in 1954 and reopened as the TDT five years later. The TDT's story is covered separately.



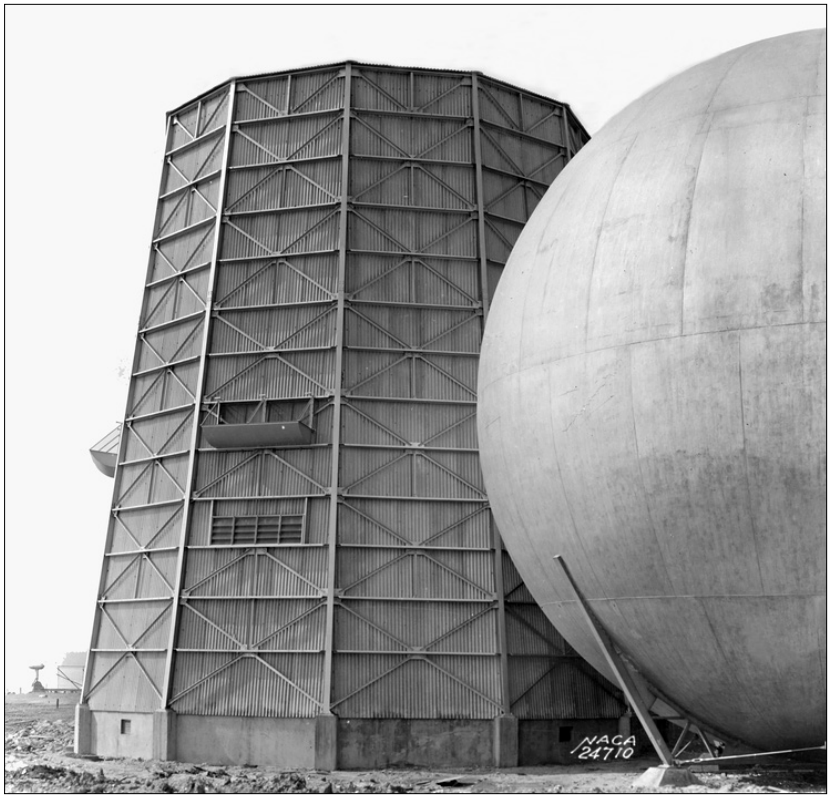
This 6-inch pilot tunnel, seen here in 1940, was built to test and refine the 19-Foot Pressure Tunnel's design prior to construction. (Photo credit: NASA LRC-1940-B701_P-19306)

This 1939 view of the 19-Foot Pressure Tunnel's open test section shows a flying boat model mounted for testing. The model's wingspan appears to be approximately 10 feet. (Photo credit: NASA LRC-1939-B701_P-17572)

The 19-Foot Pressure Tunnel's main drive motor components were shipped from the manufacturer, Crocker-Wheeler, by rail. Here two of Langley Field's 0-6-0 steam locomotives are about to move the two flat cars over track laid directly to the tunnel. Track served most of the base during the 1930s. (Photo credit: NASA LRC-1938-B701_P-10534)

The 19-Foot Pressure Tunnel presented an impressive sight shortly after its completion in June 1939. Unfortunately, its performance fell well short of impressive. (Photo credit: NASA LRC-1939-B701_P-17480)

20-FOOT VERTICAL SPIN TUNNEL



Exterior view of the 20-Foot Vertical Spin Tunnel in 1941. The louvered grills maintain atmospheric pressure in the tunnel during operation. (Photo credit: NASA LRC-1941-B701_P-24710)

SIGNIFICANCE

The 20-Foot Vertical Spin Tunnel (20-Foot VST), also known as the 20-Foot Free-Spinning Tunnel, was the NACA's third wind tunnel built specifically to study the free-spinning characteristics of airplanes. It was built as a permanent replacement for the experimental 15-Foot Spin Tunnel (15-Foot ST), and it demonstrated how proven technologies could be merged into a new design with a high degree of confidence. Its rotary balance, installed in 1945, was one of the earliest uses of strain gages in aeronautical research.

DESCRIPTION

The 20-Foot VST, Building 645, is a stand-alone structure just east of the FST in Langley's East Area. Unlike its predecessor, the 15-Foot ST, this tunnel's outer walls served as part of its structure and as the outer wall of its return duct, so it did not need to be enclosed within a building. Its appearance is that of a plump silo approximately 75 feet tall and 66 feet across at its base. Dodecagonal in plan, its 12 tapering walls are sheathed in corrugated asbestos-cement panels mounted on an external steel frame. The tunnel

has 13 rows of panels, and a 12-gored, peaked roof tops the structure. Alternating walls have ventilation grills located in the fourth and sixth panels above the concrete foundation. On the north side, an elevated, enclosed tunnel leads from the 20-Foot VST to Building 646, which contains support offices and shops. This provides access to the tunnel's test chamber.

The 20-Foot VST is a vertical wind tunnel with its flow upward through a 12-sided test section at its core. One-half of the test section walls are windows, some of which open, through which models are launched and film or video documentation is made. As in the 15-Foot ST, most tests are made with free-flying models supported by the upward column of air. Between the test section wall and the inner wall of the return duct, a floor encircles the test section at an elevation of 41 feet, 9.25 inches. An 11-foot-diameter, three-blade propeller fan near the top draws air through the test section and propels it through two sets of turning vanes down into the annular return duct that forms the outside of the structure. Another set of vanes at the base smooths the flow and redirects it back to the test section. The usable portion of the test section is 25 feet high. Above and below it are nets to prevent models from hitting the fan or falling out of control. The propeller is driven by a 400-horsepower electric motor, although it can produce as much as 1,300 horsepower for short periods to provide rapid accelerations. The tunnel's speed can be varied from 0 to 90 feet per second (0 to 61 miles per hour) with acceleration rates of –25 to 15 feet per second squared.

The 20-Foot VST's equipment currently includes a second-generation rotary balance for instrumented tests of fixed models in preset spin patterns. Visible-light video and infrared data-acquisition cameras record free flights, with the eight infrared cameras tracking the motion numerically.[89]

HISTORY

With the success of the 15-Foot ST and a growing interest in aircraft spin studies, the NACA built yet a third spin tunnel at Langley on the eve of World War II. The 20-Foot ST incorporated all that had been learned in the 5-Foot VWT and the 15-Foot ST. While the 20-Foot VST looked like nothing that had preceded it, none of its elements were really new, but how Oscar Seidman and his design team combined them was. In the process, they demonstrated how proven technologies could often be merged into a new design with a high degree of confidence.

Like the two previous vertical tunnels, this one used a vertical air flow to support a spinning model, but the new tunnel was a closed-circuit design. A large propeller, driven by a 400-horsepower (1,300-horsepower short-time rating) electric motor, drew air upward through a center column containing the test section. At the top, turning vanes directed the air out and downward through an annular return duct. Straightening vanes at the bottom stabilized the air as it started back up the central column. Unlike the two previous vertical spin tunnels at Langley, this one featured a closed test section.

So that flat windows could be used, its cross section was that of a dodecagon, a shape that reasonably approximated a circle as far as air flow was concerned. As with all spin tunnels, the air speed was not very fast—a maximum of 61 miles per hour—but higher speeds would have been of no use in this kind of research.

The tunnel opened in March 1941, just in time for the onslaught of test programs during World War II. Langley's 15- and 20-foot spin tunnels saw just about every American airplane design produced during the war, with over half of those designs being modified to enable practical spin recovery based on spin tunnel test results. The number of lives saved will never be known.

The free-flight testing procedure is similar to the one proven in the 15-Foot ST, but the models are usually flung into the airstream much like one would toss a flying disc to give it an initial spin. The models initially were larger, and often more complex, than their predecessors. Improvements in radio control and remote servos during and after the war made remote control practical, and Langley engineers devised ways to incorporate it into spin models. Jet airplanes with swept wings introduced some different spin characteristics, but the 20-Foot VST easily handled them, even planes like the innovative XB-35 flying wing. It has also tested ways that parachutes can be used to aid in spin recovery.

While free-flight tests revealed the spin and recovery motions qualitatively, by the 1940s engineers also wanted quantitative data they could use to understand and better predict aircraft spin performance and incorporate that knowledge into new designs. Acquiring such data required some kind of balance, so they drew upon Langley's earlier experience with a rotary balance in the 5-Foot VWT and built one for the 20-Foot VST. It was mounted to one side of the test section on an arm that would swing to the tunnel's centerline. At the end of the swing arm was a motor and rotating model-support arm. The model was secured to a support block that used strain gages to measure the aeronautical forces and moments. New at the time, strain gages replaced the large balance frames and multiple scales previously needed in most wind tunnels within a decade. Angle of attack, sideslip angle, and spin radius were all adjustable, and counterweights balanced the rotating apparatus. Rotation was up to 200 revolutions per minute.[90]

Instrumentation and data collection in the 20-Foot VST became increasingly electronic and automated during the NASA era. As many as four high-resolution video cameras can record free-flight tests. Using up to eight infrared data-acquisition cameras, retro-reflective targets on the model are referenced to a coordinate system to yield numerical position, velocity, and acceleration data for further analysis. Using dynamically scaled models in free flight, extreme-attitude and out-of-control flight modes such as tumbling can also be examined.[91]

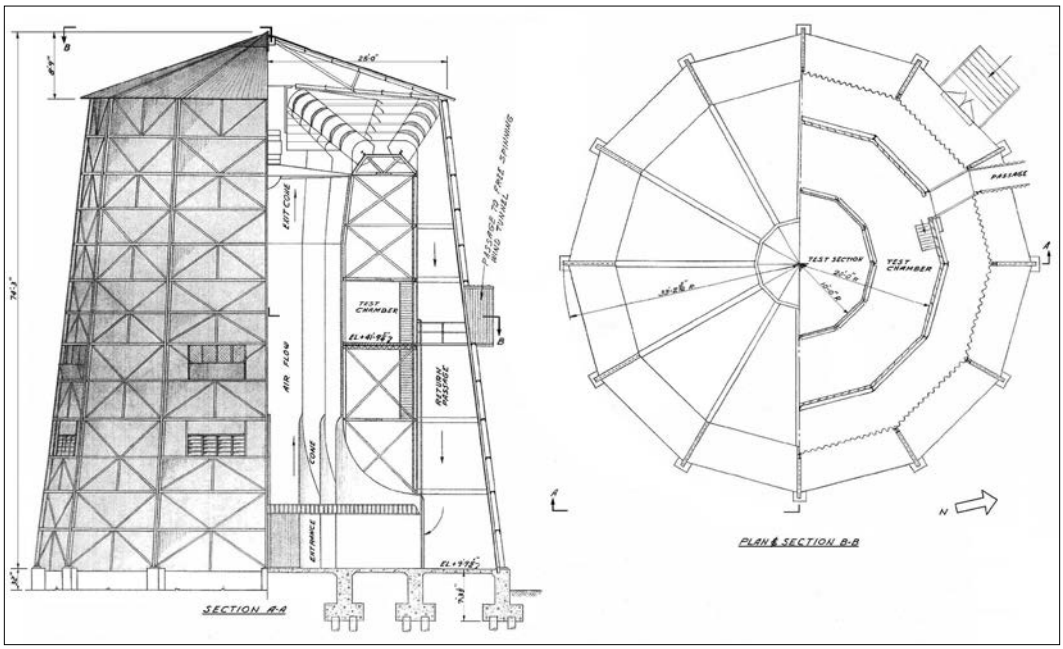
To improve the efficiency of tests with balance-mounted models, a second rotary balance replaced the first one during the 1970s. The first rotary balance, while innovative in its use of strain gages, mounted those strain gages in a block external to the model. This made it difficult to obtain repeatable data and complicated data reduction.

Consequently, this balance saw little use, even though the need for one remained. The new rotary balance operates much like as its predecessor, but it features improved instrumentation and controls. By the 1970s, strain gage technology had advanced to the point that they could be an integral part of the model attachment strut, thus eliminating unwanted mass and greatly simplifying data reduction. Additionally, the new design allows more test parameters, particularly angle of attack, to be remotely changed during operation, and it allows for static pressure measurements from the model.[92]

When the U.S. Army Air Corps found itself in need of a facility to evaluate parachutes and investigate spins at Wright Field in Dayton, Ohio, engineers there looked to the 20-Foot VST for their model. They built a 16-foot vertical tunnel in 1943 that was functionally identical to the Langley tunnel. The Wright Field tunnel has since been closed, leaving the 20-Foot VST as the only American vertical spin tunnel currently in research service.[93]

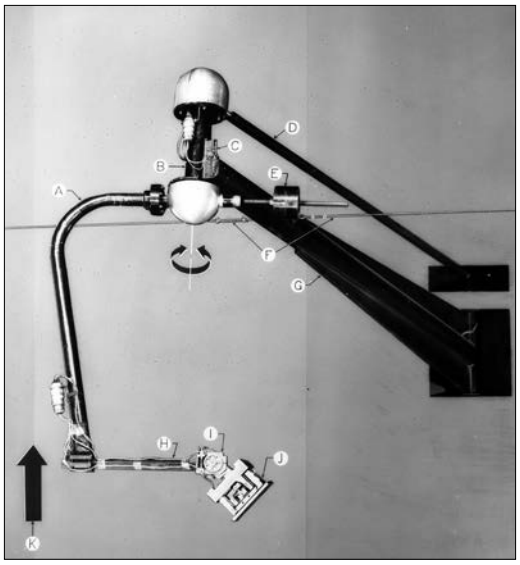
The 20-Foot VST is scheduled for demolition once construction and testing of the new Flight Dynamics Research Facility (FDRF) have been completed, currently scheduled for 2025.

This 1987 view shows a spin-recovery parachute for a proposed military trainer being tested in the 20-Foot Spin Tunnel. Videotape recording had replaced movie film. (Photo credit: NASA LRC-1987-B701_P-08561)



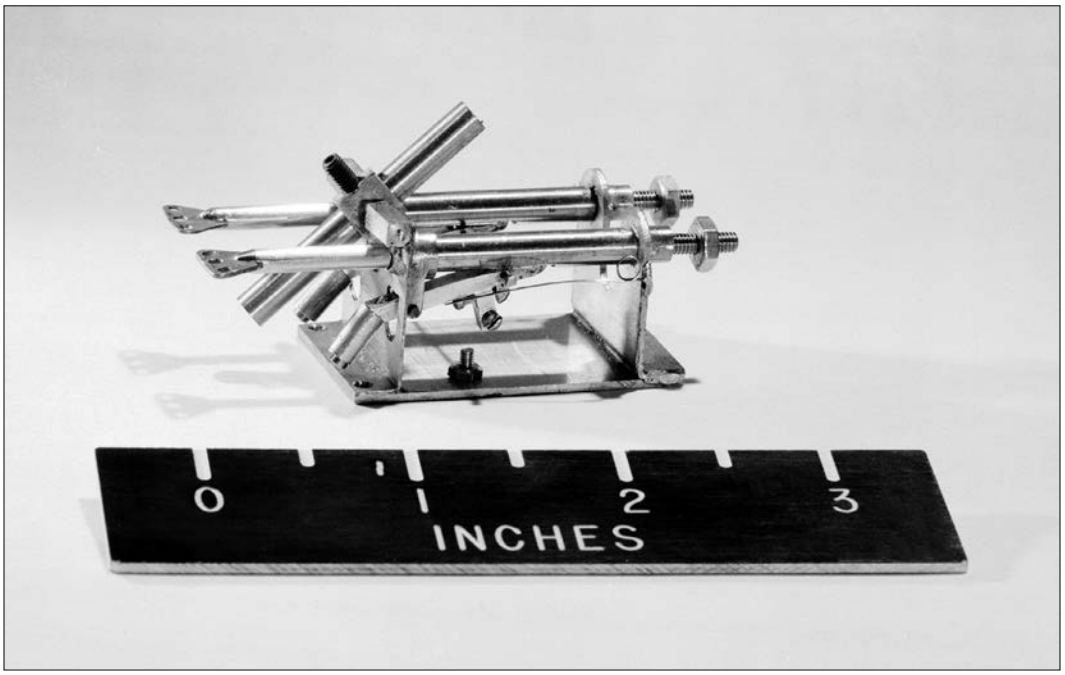
This drawing shows the construction, annular return flow path, and test section configuration of the 20-Foot Spin Tunnel. Note the elevated passage to the test chamber from Building 646. (NASA drawing)

This view shows a model during a free-spinning test in 1941. Note the technician filming the test with a movie camera and the model catch net below. (Photo credit: NASA LRC-1941-B701_P-25819)



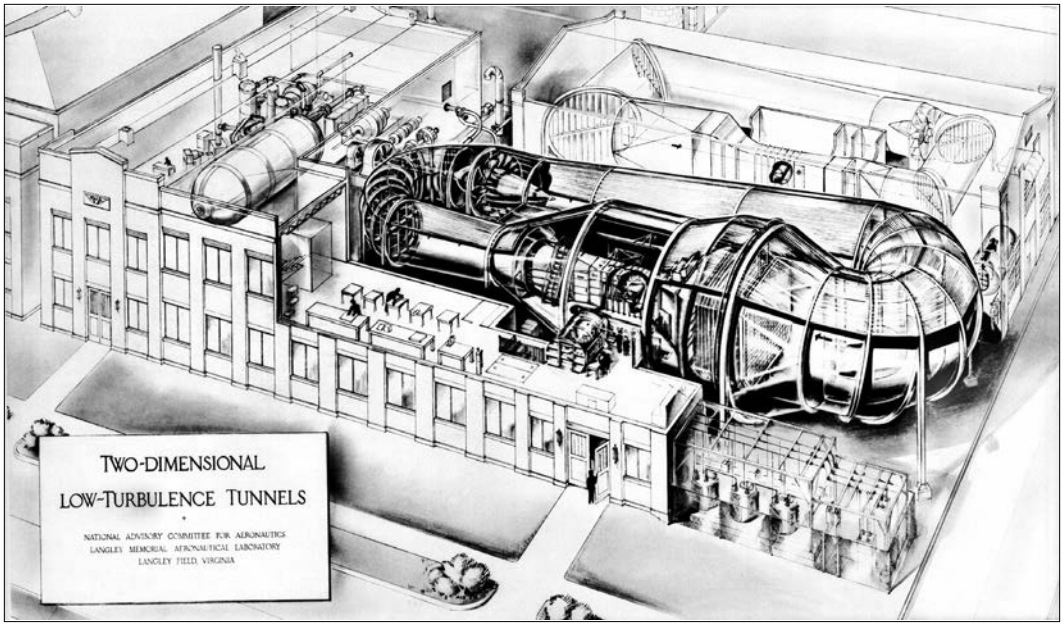
This rotary balance, installed in 1945, allowed force and moment measurements of a model mounted at J. The spin rate, radius, and angle were adjustable. (Photo credit: NASA LARC-1950-B701_P-64905)

Looking down into the test section of the 20- Foot Spin Tunnel at a free-spinning model in 1994. (Photo credit: NASA LRC-1994-B701_P-07382)



This servo device installed in a model moved its control surfaces as directed by radio commands from the test engineer. (Photo credit: LRC-1952-B701_P-76471)

LOW-TURBULENCE PRESSURE TUNNEL



This 1946 phantom drawing shows the Low-Turbulence Pressure Tunnel in the center with its predecessor, the Low-Turbulence Tunnel, in the upper right. The model-preparation room and test chamber airlock are on the second floor of the foreground building. The large air reservoir on the left was originally the Variable-Density Tunnel's pressure vessel. (Image credit: NASA LRC-1946-B701_P-49443)

SIGNIFICANCE

Completed in May 1941, the Two-Dimensional Low-Turbulence Pressure Tunnel (LTPT) was the NACA's first tunnel to combine the turbulence-reducing features proven in the Low-Turbulence Tunnel (LTT) with pressurization to achieve both high Reynolds numbers and a smooth flow. It was also the earliest NACA steel wind tunnel to be built primarily outside of a building, and its basic structural design was utilized for many subsequent tunnels. The LTPT's gored turns also served as the prototype for the 12-Foot Pressure Tunnel built at the Ames Aeronautical Laboratory in 1946.

DESCRIPTION

The LTPT was the second of the NACA's "outside" wind tunnels, with all of its tunnel circuit exposed to the weather rather than being enclosed within a building.[94] The tunnel was located in Langley's East Area, directly behind Building 60-B (now 582-A). Built to be a permanent facility based on the successful design of the cheaply constructed LTT, the LTPT was constructed entirely of steel that was fabricated by the Pittsburgh-Des Moines Steel Company. It was the third wind tunnel contract for a company beginning to build a substantial niche market in wind tunnels.[95]

The LTPT is a single-return, closed-circuit wind tunnel measuring approximately 146 feet long by 58 feet at its widest part. Externally, it exhibits a circular cross section

around its entire circuit. The entrance cone, rectangular test section, and initial portion of the exit diffuser are located within a 22-foot-diameter outer shell, with the settling chamber inside a 26-foot-diameter bulge in the outer shell. This outer shell forms the test chamber and serves as the pressure vessel in the test-section area. The 7.5- by 3-foot test section is referred to as "two-dimensional" because lateral airflows are inconsequential for many of the tests, thanks to the narrowness of the test section. It is preceded by an entrance cone with a 17.6:1 contraction ratio (the ratio of settling chamber to test section cross-sectional areas), only a little less than that used in the LTT. The test chamber is accessed through an airlock from the second floor model-preparation room of Building 582-A, though no one is permitted inside at any pressure greater than 4 atmospheres. The airlock's circular high-pressure door opens into the test chamber.[96]

The LTPT's settling chamber, located in the bulging portion of the tunnel, contains a cooling coil, a 60-mesh screen, and 11 30-mesh screens. The double-row cooling coil uses water cooled in a cooling tower outside and circulated at the rate of 1,000 gallons per minute. The anti-turbulence screens were woven using 0.0065-inch-diameter phosphor bronze wire.

To prevent excessively high humidity in the compressed tunnel air, a blower pulls a portion of the tunnel's air out and through a direct-expansion refrigeration system located in the test chamber. Its condenser uses cooling tower water, and condensation passes out of the pressurized tunnel through a trap. This unit also furnishes some cooling of the test chamber when people are working in it.

The LTPT's circuit was constructed of steel plate between ¾ inch and 2 inches thick, with external structural hoops. Some of these structural hoops had integral legs that transmitted the tunnel's weight to concrete foundations. The LTPT featured unusual, gored turns at both ends. Each of the LTPT's two, approximately 180-degree turns had seven segments, making the angle between any two adjacent segments about 22.5 degrees. All of the joints were arc-welded to ensure the tunnel was airtight. A metal awning over the tunnel between the fan and settling chamber shielded it from excessive solar heat, and both the awning and tunnel were painted white to further reduce radiant heat absorption.

The tunnel's single fan was located in the long return leg, just after the first turn. It was turned by a Westinghouse Electric 2,000-horsepower DC electric motor mounted on a pedestal in a drive room of Building 582. A General Electric motor-generator set in the same area furnished DC power to the drive motor. The motor's speed controls were located adjacent to the test section air lock on the second floor of Building 582-A. The drive shaft and hub for the 13-foot-diameter fan were enclosed in a streamlined fairing, and the shaft penetrated the tunnel wall through a gland seal. The fan's 20 blades were manufactured from aluminum.

Building 60-B (now Building 582-A) in Langley's East Area was built as an extension of existing Building 60-A (now Building 582), which was the metal structure originally built to house the VDT. The new construction enlarged Building 60-A and faced its

exterior with brick in a design that matched the 60-B addition. Renumbered after World War II, both structures have two interconnected floors, although the original portion of Building 582 retains its high bay and partial mezzanine. The two main entrances feature cast concrete inserts above double doors that identify their respective tunnels.

Until it was declared unserviceable in 1978, the VDT's pressure vessel served as the main air reservoir between the LTPT and its air compressors. Four vertical reservoirs located outside Building 582 have served the LTPT since then. LTPT property records specify a value for only "built-in mechanical equipment," so it is not known if new compressors were purchased with the LTPT. The VDT compressors may have been utilized for some time. Two reciprocating compressors, manufactured by Chicago Pneumatic and Worthington Pump & Machinery, are now located in the space once occupied by the VDT compressors in Building 582.[97]

HISTORY

The Low-Turbulence Tunnel, built as an economical means of testing the validity of Eastman Jacobs's arguments about the deleterious effects of turbulence in wind tunnels, began to prove him right within weeks of its initial operation in 1938. Its dramatically high contraction ratio, multiple smoothing screens, and boundary-layer removal fans were very effective and produced the lowest degree of turbulence yet seen in a wind tunnel, and the measurements taken in the LTT, especially those of drag, exhibited an excellent correlation to in-flight data, at least at low speeds and Reynolds numbers. As Jacobs knew from his experience with the VDT, pressurizing the tunnel would raise Reynolds numbers to useful levels, but the LTT had been built as an atmospheric tunnel to keep its cost low at a time when few realized just how significant turbulence was or were willing to invest much in its study.

The LTT's impressive results gave the NACA's Director of Research George Lewis the ammunition he needed to win funding for a pressurized low-turbulence tunnel from Congress in 1938. Design and construction of the LTPT began shortly after Congress approved funds for it, and the tunnel entered service in May 1941. Its total cost was just under $612,000.[98]

The LTPT's design engineers, led by Eastman Jacobs and Ira Abbott, had some new challenges on their hands. Although the new LTPT would incorporate the proven turbulence-reduction methods of the LTT, it would also be a pressure vessel operating at pressures of up to 10 atmospheres (146 psi). This virtually dictated steel construction and a circular cross section to minimize stress concentrations at corners. The test section was made in the same 7.5- by 3-foot rectangular configuration as the one in the LTT, but the LTPT's test section was housed inside a plenum with a circular cross section that served as the pressure vessel. Instead of the four 90-degree corners more commonly used in wind tunnels, each of the LTPT's two, approximately 180-degree turns has seven segments, or gores, making the angle between any two adjacent segments about 22.5 degrees. This was done to reduce the stresses from pressurization on each joint. (The

engineers built and hydrostatically tested a small model of one such turn to validate the design.) All of the joints were arc-welded to ensure the tunnel was airtight, and upon completion, the entire circuit was filled with water and hydrostatically tested to prove its structural integrity at 225 psi, 1.5 times its service rating of 150 psi.

The guide vanes in the turns contributed a little to turbulence reduction, but the main reason for using them was to minimize stresses by reinforcing the joints between gores. Jacobs and Abbott made the splitter vanes just ahead of the settling chamber continuous for still greater structural strength in this large-diameter portion of the tunnel.

A 2,000-horsepower drive motor was chosen to give a maximum speed of 0.5 Mach, and the engineers used a Ward-Leonard control system to enable a fully controllable speed range between 38 and 381 miles per hour (0.05–0.5 Mach). Employing both pressure and speed, the tunnel can generate a maximum dynamic pressure of 785 pounds per square foot and Reynolds numbers of up to 15×10^6 per foot of model chord. Air-exchange towers cannot be used for heat control in pressurized tunnels, so Jacobs and Abbott installed a two-row cooling coil in the settling chamber. This was not intended for precision temperature control, but rather to maintain reasonable conditions, and it keeps the LTPT operating in the range of 60–120°F (520–580 Rankine).

Jacobs and Abbott also installed two blowers inside the test chamber, each driven by a 100-horsepower motor. These blowers provided considerable flexibility in test configuration. One or both were commonly used for boundary layer extraction along the walls, but one or both could be set up to supply external air to the model when needed.

Turbulence measurements were made soon after the tunnel entered service using equipment from the National Bureau of Standards, and these measurements made it evident that the engineers had achieved very smooth flow. Subsequent checks over the years have indicated little, if any, change. The LTPT's maximum velocity fluctuations vary between 0.025 and 0.30 percent, depending on speed and pressure, although they are less than 0.10 percent over most of the operating envelope.[99]

Jacobs and Abbott designed the LTPT primarily to test model airfoils that spanned the test section's 3-foot width. Airfoil models are usually mounted on an adjustable angle-of-attack mechanism, and lift and drag forces are calculated from floor and ceiling pressure measurements. Originally recorded off manometers, these pressures are now measured and recorded electronically. During the LTPT's early years, when pitching moments were needed, the technicians mounted the airfoil on a unique, torque-rod–style balance fastened to the test-section wall. The torque rod penetration through the tunnel wall included an inflatable seal. It was deflated for angle-of-attack setting changes, and its flexibility introduced no detectable error, even during minor movements of the airfoil.

Changing demands during the LTPT's life have resulted in numerous additions to the stable of model mounting hardware and test instrumentation. The LTPT gradually began to perform more three-dimensional testing, with aircraft models mounted on a sting support and balance. When used, the sting attaches to a streamlined vertical post on the tunnel's centerline. It uses strain gages to measure loads, with their data

recorded by electronic equipment, including a MODCOMP Classic data acquisition system. Models with wingspans of up to 2 feet can be tested this way, and they have included the Space Shuttle orbiter and various conceptual designs for possible successors. Additionally, the LTPT was a good venue for basic research into such topics as Taylor-Goertler Instability.[100]

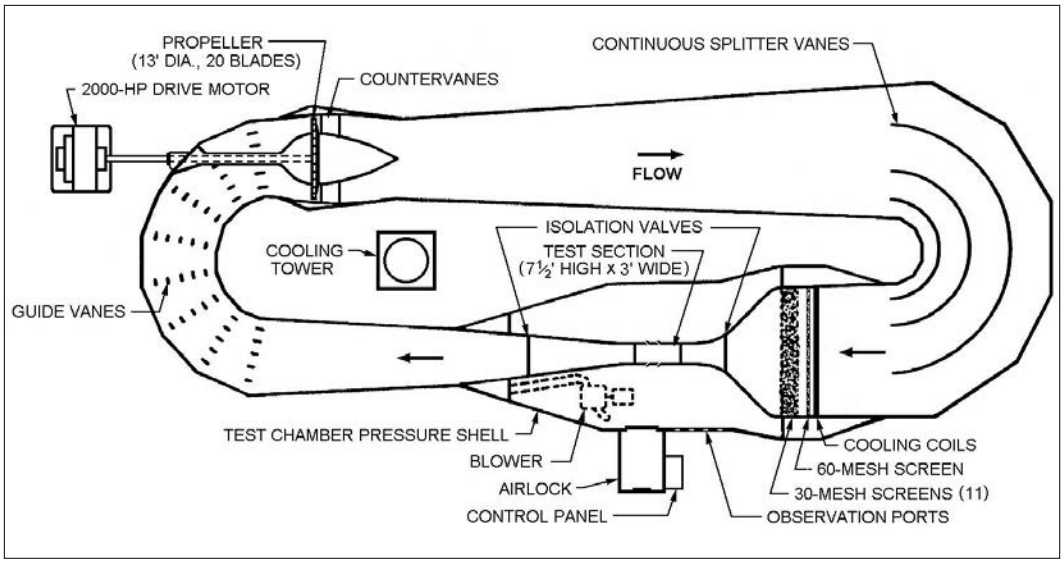
Perhaps the most intriguing tests in the LTPT began with a request from the Department of Commerce in 1943, and the resulting wind tunnel tests consumed far more time than the actual airplane ever spent in the air. The plane was the Hughes-Kaiser HK-1 Hercules (also known as the Spruce Goose), a gigantic wooden flying boat that flew only once for about one mile. Langley did both hydrodynamic and aerodynamic testing on a 1/40–scale wing-hull model and a 1/10–scale float-strut model, with the LTPT hosting the aeronautical tests. These tests revealed much about the lift and drag contributions of the fuselage and floats, including the detrimental effects to be expected from a proposed spray-reduction modification.[101]

Except for the noted improvements in instrumentation, the tunnel remained essentially in its original configuration, though it underwent a rehabilitation/upgrade project in 1980 to improve the reliability of its drive system and install new test hardware. The LTPT's control panel was always small and rather simple, but alterations in 1980 and after gave it an appearance quite different from its original configuration.[102]

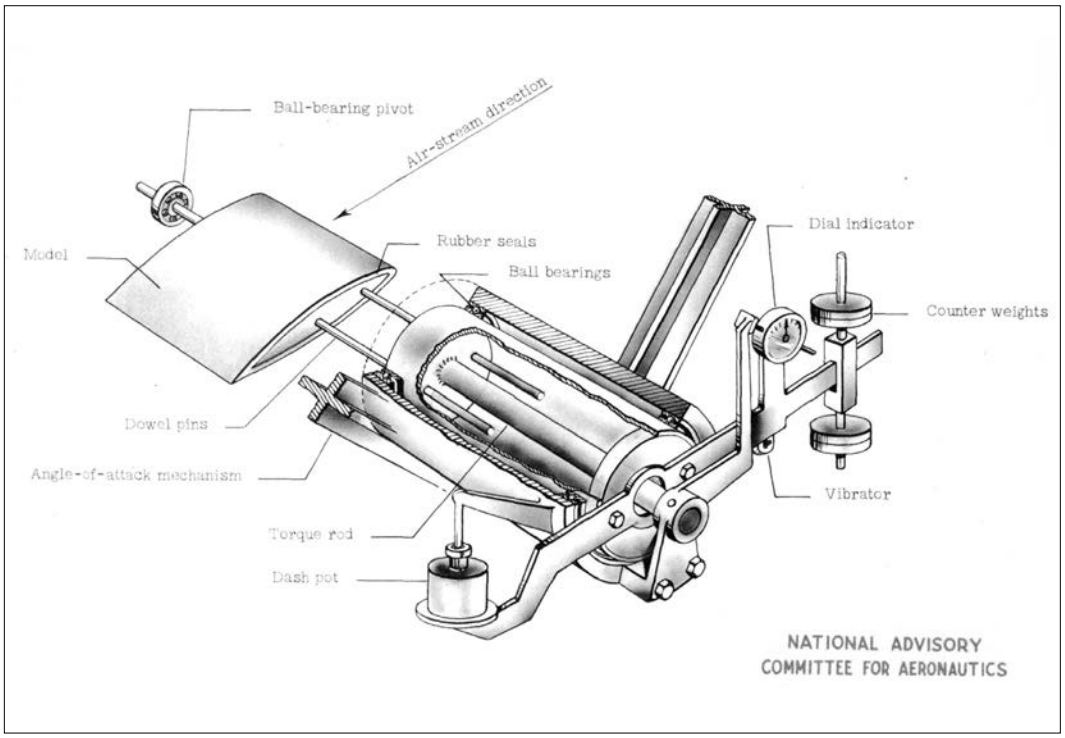
By furnishing the capability to test models at fairly high Reynolds numbers in a very smooth airstream, the LTPT quickly became a valuable addition at Langley after it opened in 1941. The LTPT remained in use for years, and a number of modifications were made to improve its versatility. Much of the later research sought to improve the efficiency of integrating engines into military and commercial aircraft airframes.

Langley ceased operation of the LTPT following a drive motor fire in 2006. The facility was demolished in 2014.

The Low-Turbulence Pressure Tunnel is prominent in this 1986 aerial view of the NACA's first group of research facilities in Langley's East Area. (Photo credit: NASA LRC-1986-B701_P-06751)



This plan drawing shows the gored turns, large-contraction entrance cone, and multiple screens used to reduce turbulence in the Low-Turbulence Pressure Tunnel's test section to a minimum. The two isolation valves allowed the test section to be depressurized for personnel access without depressurizing the remainder of the tunnel, saving considerable time and energy between test runs. (Image credit: NASA TP-2328, Fig. 2)



This drawing shows the unusual torque-rod balance used with airfoil models in the Low-Turbulence Pressure Tunnel. Only the model was exposed to air flow inside the test section. (Image credit: NACA TN-1283, Fig. 22)

This small model of one of the Low-Turbulence Pressure Tunnel's gored turns helped validate the pressure vessel design. In this 1938 photograph, the model is being prepared for a hydrostatic test. (Photo credit: NASA LRC-1938-B701_P-15428)

A model of the proposed X-33 space plane prototype, shown here mounted on a sting balance in 1997, underwent significant testing in the Low-Turbulence Pressure Tunnel. (Photo credit: NASA LRC-1997-B701_P-01039)

16-FOOT HIGH-SPEED TUNNEL
16-FOOT TRANSONIC TUNNEL

This 1942 photograph shows the 16-Foot High-Speed Tunnel shortly after it was completed in 1941. (Photo credit: NASA LRC-1942-B701_P-28410)

SIGNIFICANCE

The 16-Foot High-Speed Tunnel (16-Foot HST) was the first wind tunnel built in Langley's West Area and the last American wind tunnel to open before the nation's entry into World War II. Although a shortage of available electricity in the area limited its power and maximum testing speed, its dynamometers allowed it to effectively test full-scale engine nacelles and propellers during the war.

After a major rebuilding, the tunnel became the NACA's second wind tunnel with slotted walls for transonic operation, and the first very large one with this capability. Renamed the 16-Foot Transonic Tunnel (16-Foot TT), it was repeatedly upgraded and used extensively for aircraft and spacecraft aerodynamic testing from 1950 through 2004.

DESCRIPTION

The 16-Foot TT was a large, externally braced, steel wind tunnel located in Langley's West Area. When built as the 16-Foot HST in 1941, it was the NACA's second wind tunnel constructed in this manner (the first having been the 19-Foot Pressure Tunnel). Its rebuilding into the 16-Foot TT in 1950 utilized the same design for the new portions, giving it a homogeneous appearance. The original two-story brick building measuring approximately 30 feet by 105 feet on the tunnel's north side contained offices and model-preparation shops. Brick additions on the building's north side during the 1950s and 1960s approximately doubled its floor area. A 30-foot-wide high-bay area, also of

brick, rises another 20 feet above the back center of the building. It originally extended farther south to cover the test section and provide space for model handling, but this overhead service area was enlarged significantly with a metal-clad addition during the 1950 conversion to the 16-Foot TT.[103]

As built, the 16-Foot HST measured 140 feet by 360 feet, plus the office and air-exchange tower footprint. This air-exchange tower, which exchanged 5 to 20 percent of the tunnel's air with outside air to control temperature, rose above the tunnel approximately 40 feet ahead of Corner 3. Approximately 40 by 100 feet in plan and 75 feet tall, it featured a roof exhaust grill and intake louvers around its upper sides. Because of the tunnel's 58-foot-diameter settling chamber, its centerline was approximately 30 feet above the ground throughout the circuit. This centerline height was retained during the 1950 rebuilding, but the west end was extended about 50 feet to reduce the flare in the diffuser and improve flow quality. The resulting circuit measured 930 feet along its centerline. Early photographs seem to indicate that the tunnel was originally painted silver, but it was white in later decades. Either color is effective in minimizing the amount of solar heat buildup in the tunnel.[104]

The original design located the dual 8,000-horsepower drive motors and fans in a single nacelle just after the second turn, but this changed completely during the conversion. Two 30,000-horsepower motors driving 34-foot-diameter, counter-rotating fans were mounted in the new section between Corners 1 and 2. The two fan shafts, which were enclosed in a continuous streamlined fairing, extended from each fan out the corners to the motors. The entire drive system was mounted at the tunnel's centerline height atop a trio of concrete pedestals, with the motors housed in semi-cylindrical enclosures.[105]

As in most modern wind tunnels, the 16-Foot TT's diameter gradually increased from 16 feet (actually 15.5 feet across the flats of an octagon) in the test section to 34 feet in the fan section, and ultimately to 58 feet in the settling chamber. This yielded a 13.3-to-1 contraction ratio into the test section. Two antiturbulence screens in the settling chamber also helped smooth the flow. A 32-foot-diameter plenum surrounded the test section. After 1961, an air-extraction system could remove up to 956,000 cubic feet of air per minute from the plenum, which allowed the tunnel to achieve a maximum speed of Mach 1.3. This system was located in the central courtyard, with its 36,000-horsepower motor and compressor inside a rectangular metal building.[106]

HISTORY

Although the NACA had received substantial funds and built several new wind tunnels at Langley during the depression-ridden 1930s, it was not alone in doing so. Several European nations, the most worrisome being Fascist Italy and Nazi Germany, had started constructing new aeronautical laboratories of their own or adding to existing ones. These new Langley tunnels were badly needed, since the "design revolution"[107] had begun to completely transform aircraft design and capabilities. Metal started to

replace wood and fabric, and structural design started to reflect the properties of the new material. Large, internally braced wings became practical, eliminating the wasteful drag of struts and wires. Performance-enhancing devices, such as wing flaps and retractable landing gears, helped expand the envelope as well, and new engine and propeller designs dramatically increased the available power. This revolution demanded research tools well beyond the capabilities of those in existence.

For a time, these European nations substantially outbuilt the United States, but the NACA kept watch on their activities through its Paris office, led by John Jay Ide. Ide visited most of these new facilities and submitted detailed reports to the NACA Director of Aeronautical Research, George Lewis. Concerned over Ide's reports, Lewis visited Europe to see for himself in 1936. Although an isolationist Congress was slow to act, the NACA finally secured $11 million for a major expansion in 1939. The largest portion of these funds allowed the NACA to begin construction of a new West Coast laboratory, named the Ames Aeronautical Laboratory, in 1940, but a $1.5 million appropriation initiated a major change in the look and capability of the Langley Laboratory as well.[108]

Both Ames and Langley soon began to build 16-foot high-speed tunnels. They were quite similar, except for power. Once again, the shortage of power in Hampton limited the Langley 16-Foot HST to 16,000 horsepower and, thus, about Mach 0.7. (While substantial, this was less than 60 percent of the power installed in its counterpart at Ames.) The Langley tunnel was authorized a few months before the one at Ames, but construction proceeded at a slightly slower pace, so it entered service a few weeks later. One of the reasons is that the 16-Foot HST broke new ground—quite literally—at Langley. Between expansions of both the NACA and Army Air Corps facilities, there simply was little room left for a new wind tunnel on the east side of Langley Field, so the NACA looked west to find room on the other side of the field. The 16-Foot HST was a large machine, and it became the first wind tunnel built in the West Area. It was also the last wind tunnel to go online in 1941, opening only two days before the Japanese attack on Pearl Harbor.[109]

Knowing that electrical power was in short supply, David J. Biermann and Lindsey I. Turner, Jr., the lead design engineers, had developed the rationale for the 16-Foot HST carefully. Clearly it would not be useful for the most advanced aerodynamical studies—the Ames tunnel was for that—but the 16-foot size would be perfect to investigate engine-cooling problems. Years earlier, the NACA cowling had significantly improved the cooling of air-cooled radial engines and lowered drag as well. By the late 1930s, these early single-row radial engines had grown into two-row models and cooling the second row of cylinders emerged as a major problem, one that no existing wind tunnel had both the size and speed to help solve.[110]

Propeller research was another serious need, particularly to determine the optimal settings for variable-pitch propellers under various conditions. Variable-pitch propellers had been developed during the 1930s, but much remained to be learned about how they could best be used throughout the flight envelope. The 16-Foot HST's power would

allow it to cover the entire speed range of propeller-driven planes and make it ideal for propeller investigations.

With these goals in mind, Biermann and Turner's team designed a closed-circuit, atmospheric tunnel with an air-exchange tower that would maintain reasonable temperatures in the tunnel as well as replace a significant portion of engine exhaust gas with fresh air during operation. They chose to use a design similar to one pioneered by the Wright Brothers Wind Tunnel in 1938 at the Massachusetts Institute of Technology and employed in Langley's 19-Foot Pressure Tunnel a year later. While the 16-Foot HST would not be pressurized like these two tunnels, its large size made the externally braced, steel-shell design the best choice for strength and economy.

While not the state of the art in speed, the 16-Foot HST was well engineered and capable of useful wartime research. Equipped with 2,000- and 6,000-horsepower electric dynamometers, the tunnel could operate full-sized propellers at airspeeds of up to around 500 miles per hour. The dynamometers provided accurate measurements of the amount of power a given propeller could efficiently handle and helped determine its optimum operating conditions (revolutions per minute and pitch angle) for a variety of flight conditions. Tests of two-row radial engines operating at flight airflows with thermocouples mounted to measure the temperatures at critical spots helped engineers design and adjust internal baffles to alter the airflow and better cool hot areas. Although the 1944 opening of the Altitude Wind Tunnel at the Lewis Flight Propulsion Laboratory in Cleveland focused attention on it as the NACA's premier engine-testing tunnel, the 16-Foot HST did not drop out of the picture. It continued to host engine-cooling tests until about 1947, as well as propeller tests until at least 1953, generating valuable data in both areas.[111]

The 16-Foot HST's position as the first wind tunnel in Langley's West Area uniquely suited it to serve as host for no fewer than five small tunnels built to inexpensively evaluate new concepts for trans- and supersonic research. Such parasitic tunnels that utilized the power, support facilities, and staffs of their hosts were not uncommon at Langley, and several have already been noted, but the number and variety supported by the 16-Foot HST during the late 1940s is unusual. Since these tunnels were often "proof-of-concept" devices, research work done in them rarely warranted technical papers, nor did the NACA publish descriptive publications. Thus, comparatively little is now known about them, but one memorandum answering an inquiry about Langley's supersonic facilities at least furnishes some basic information.[112]

The most influential of these was the Parasite Tunnel, which was built to evaluate slotted test section designs and their effectiveness in the reduction of choking near Mach 1. Designed by Vernon G. Ward, this little tunnel, which tapped into the 16-Foot HST to use its fans for draft, strongly influenced the slotted-wall modifications made to both the 8- and 16-Foot HSTs. None of these five small facilities survive.[113]

FACILITY NAME	THROAT SIZE	MAX. SPEED	BUILT
Model Supersonic Tunnel	7.5 in. × 7.5 in.	Mach 1.7	1944
Supersonic Display Tunnel	2 in. × 8 in.	Mach 1.68	1945
Supersonic Flexible-Wall Tunnel	2 in. × 4.75 in.	Mach 1.6	1946
Parasite Tunnel	12 in. diameter	Mach 1.1	1947
Supersonic Plug Tunnel	2 in. × 5 in.	Mach 1.8	1947

After World War II, however, transonic (generally defined as being between Mach 0.7 and 1.2) research suddenly became a top priority with the advent of jet-powered aircraft. As discussed in the 8-Foot HST section, choking problems prevented stable wind-tunnel operation near the speed of sound until Langley's Ray Wright developed a practical slotted-wall design in 1950. By that time, the NACA had decided to rebuild the 16-Foot HST with more power, and Section Chief John Stack included a new, slotted-wall test section in the rebuilding project to enable transonic operation.

The rebuilt tunnel, renamed the 16-Foot Transonic Tunnel, opened in 1950 with a 15.5-foot, octagonal test section and a dual-motor/fan drive totaling 60,000 horsepower. The new motors and fans were mounted on massive concrete pedestals with the motors outside the tunnel and the counter-rotating fans relocated between the first and second corners. The tunnel's west end was also lengthened to provide a longer diffuser that improved the quality of flow into the drive section. The slots were placed at the intersections of the test section wall panels, and a large plenum was erected around the test section, along with a 6-story-high metal service building. The upper three test section panels and the top of the plenum opened to allow insertion of test items. Several model mounts were provided, including a sting and sidewall supports. A hydrogen peroxide system enabled hot exhaust simulation in models of jet engines and aircraft.[114]

Researchers rapidly booked the 16-Foot TT with a wide variety of test programs, particularly programs involving jet engine inlets and exhausts, and their interactions with the airframes. Engineers learned much about how the design of these components affected the performance of both engines and aircraft.

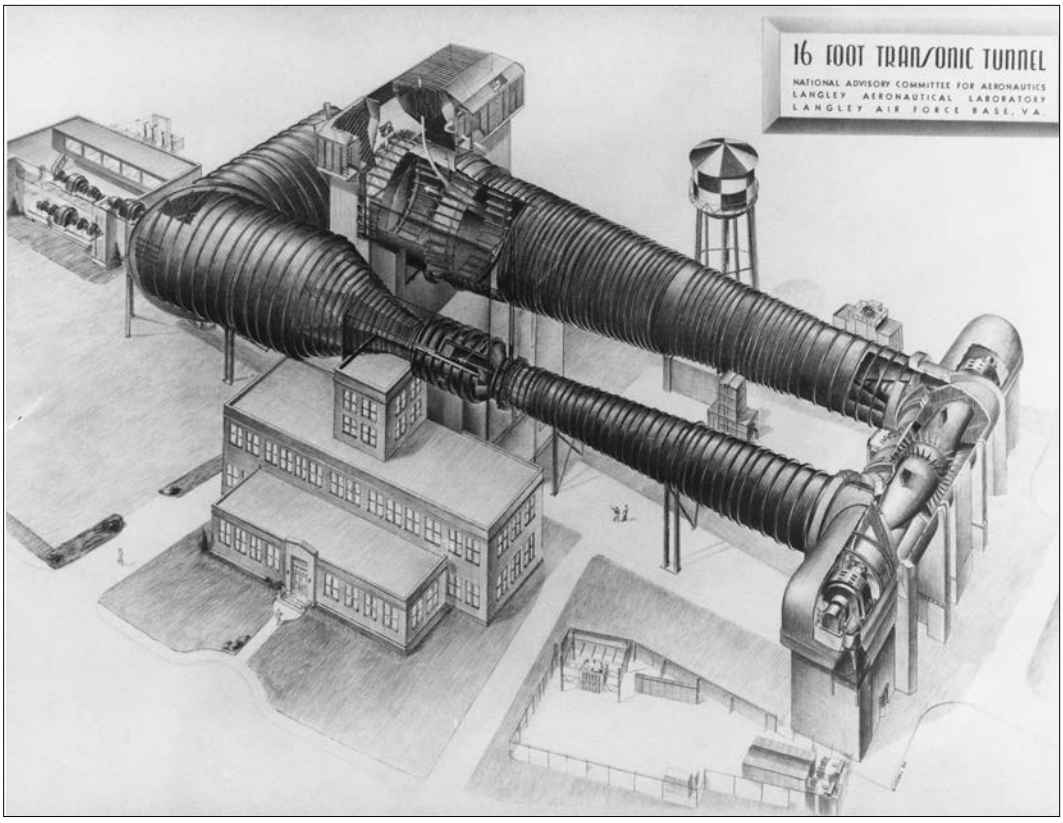
When it opened in 1950, the 16-Foot TT could reach a maximum speed of Mach 1.08, but researchers discovered that measurements above Mach 1.03 were inaccurate, due to shock waves from the model's nose that reflected off the walls. The slotted wall design was not perfect, and model blockage effects still caused significant problems near Mach 1. During the 1950s, studies indicated that air removal from the plenum and test section could help reduce these model blockage effects, and the newly created NASA approved the addition of an air removal system. Installed in 1961, an axial-flow compressor driven by a 36,000-horsepower motor extracted up to 956,000 cubic feet of air per minute—approximately 4.5 percent of the tunnel's total flow—from the plenum. This reduced the blockage effects and the total energy needed for the main drive to overcome both shock and diffuser losses, and it resulted in a maximum stable speed of Mach 1.3 without an expensive increase in the main drive power. The increased capability allowed models up to 6 feet long to be tested at speeds of at least Mach 1.15 without reflected shock interactions.[115]

Further changes to the 16-Foot TT included the addition of improved tunnel controls, new Sitka spruce fan blades, and an on-site data-acquisition system in 1977. These features were again upgraded in 1989–91 to keep the tunnel up to date.[116]

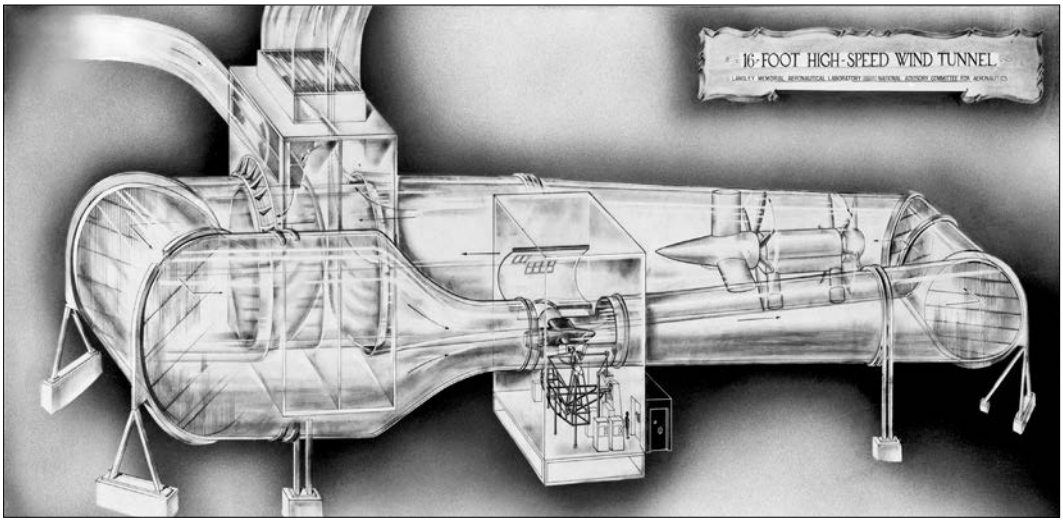
Changes to the 16-Foot TT over the years revealed that the original slot shape selected in 1950 needed further refinement to obtain optimal performance. This was especially true after the addition of the plenum air extraction system raised the top speed. Theory provided some initial guidance to these studies, but most of the refinement was an empirical process. No fewer than 11 different shapes were tried before one known as "slot shape 29" proved suitable for speeds from Mach 0.2 to 1.3.[117]

The 16-Foot TT hosted significant research programs on a variety of subjects for more than 50 years. Notable projects included engine-airframe integration studies for such planes as the F-111, F-14, F-15, B-1, and B-2; and tests of non-axisymmetric exhaust nozzles that were the precursors of those used on stealth and vectored-thrust aircraft like the F-117, B-2, and F-22.[118]

While the 16-Foot TT's bookings remained high into the 21st century, budget constraints and the availability of other tunnels with similar capabilities led NASA to close the 16-Foot TT in 2004.[119] In 2011, NASA demolished the 16-Foot tunnel circuit with the exception of the brick office building.



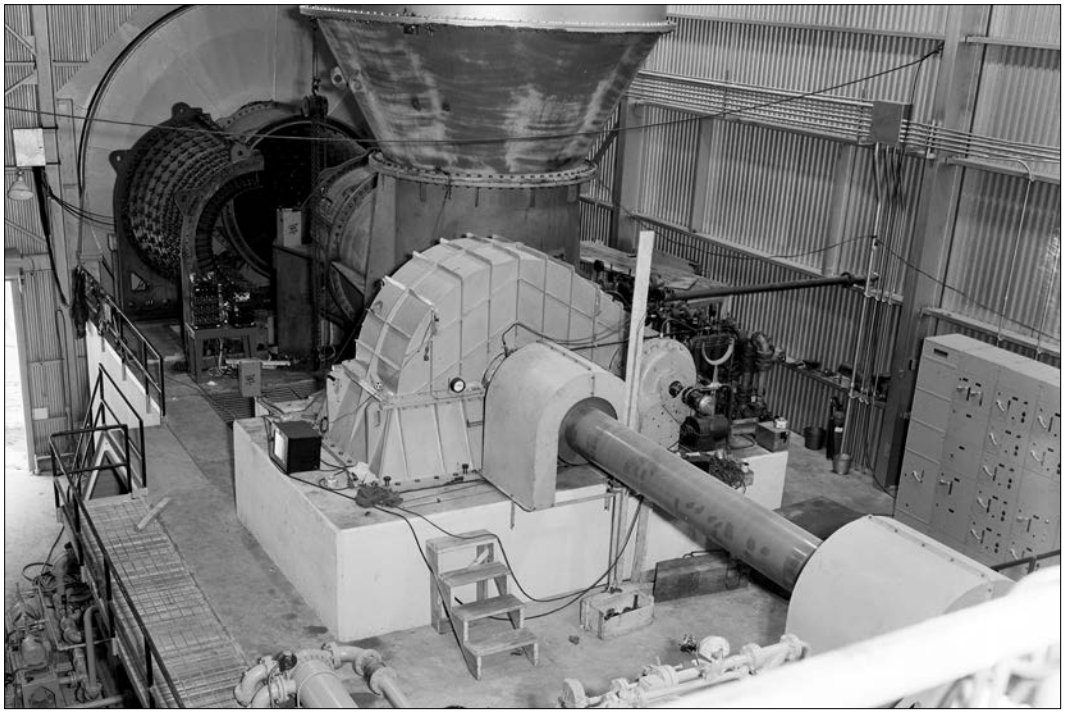
This phantom drawing of the rebuilt 16-Foot Transonic Tunnel shows the massive pedestals needed to support the two 30,000-horsepower motors and dual propeller fans, as well as the plenum installed around the new slotted-wall test section. The rebuilt tunnel entered service in 1950. (Image credit: NASA LRC-1990-B701_P-03752)



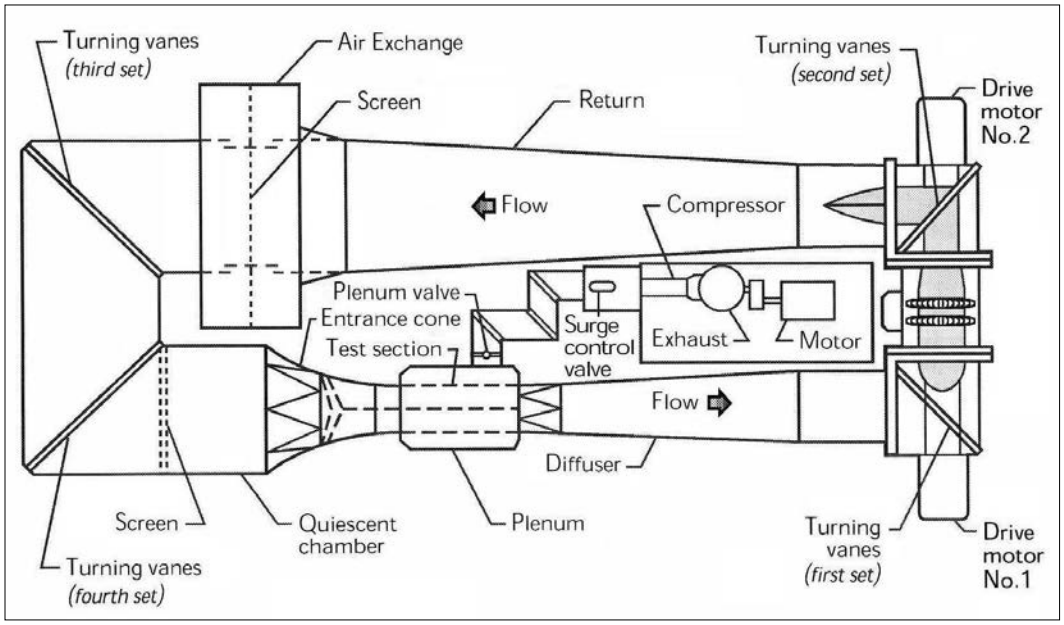
Though the 16-Foot High-Speed Tunnel, seen in this 1945 drawing, was a modern tunnel, its 16,000-horsepower drive limited the maximum speed to Mach 0.7. (Image credit: NASA LRC-1945-B701-P-48187)

An XA-26 engine nacelle and propeller in the 16-Foot High-Speed Tunnel, circa 1942. (Photo credit: LRC-1942-B701_P-30403)

These two views show the 16-Foot Transonic Tunnel's 15.5-foot octagonal test section in 1990 and 2004. The eight slots are at the intersections of the wall panels. Note how the top three panels open for model installation. Also visible are the sting model mount and its support, which can vary the angle of attack during operation, and the rectangular observation windows. (Photo credits: NASA LRC-1990-B701_P-04029 and NASA LRC-2004-B701_P-01422)



This 36,000-horsepower plenum exhaust system could extract up to 956,000 cubic feet of air per minute. The compressor is at the far end in this 1960 photograph, with its exhaust vertically upward to the atmosphere. Its motor is in the right foreground. This system also served the 7- by 10-Foot High-Speed Wind Tunnel. (Photo credit: NASA LRC-1960-B701_P-04688)



This plan drawing shows the current configuration of the 16-Foot Transonic Tunnel. The plenum exhaust system in the center, installed in 1961, improved high-transonic stability and made low-supersonic operation practical. (Image credit: NASA TM-102750, Fig. I-3)

STABILITY TUNNEL

This 1941 view of the Stability Tunnel during its construction shows its overall configuration. The steel cube next to the building is the test chamber. The top of the air exchange tower has not yet been sheathed. (Photo credit: NASA LRC-1941-B701_P-22894)

SIGNIFICANCE

The Stability Tunnel was one of several wind tunnels built by the NACA to investigate specific aspects of flight. For this tunnel, the interest was in the stability and control performance of aircraft subjected to nonuniform airstreams, such as those encountered in swirling winds and during pitch and yaw maneuvers. To suit this work, the tunnel was designed with two interchangeable test sections, one for swirling flow and the other for curved flow, making it the NACA's first wind tunnel with interchangeable test sections. Both test sections featured active components to induce the desired nonuniform flow.

The Stability Tunnel was built with an unusual balance. Mounted beneath the test section, it used conventional mechanical linkages and scales to measure forces and moments, but it was equipped with electrical transducers that transmitted the scales' data to the control room. Thus, it was an important transitional step between all-mechanical and all-electric (strain gage) balances.

DESCRIPTION

The Stability Tunnel was the second wind tunnel built in Langley's West Area. It was built across from the 16-Foot HST on West Taylor Street as Building 1149. The complex

consisted of a 2-story brick office and shop building with an exposed, steel wind tunnel on its northeast side. A steel test chamber surrounded the tunnel's test section and connected directly to the brick building.

Except for its novel, interchangeable test sections, the basic design and construction of the Stability Tunnel was similar to that of most other contemporary tunnels. Designed as an atmospheric tunnel, the Stability Tunnel employed a rectangular cross section throughout its closed circuit, except for transitions into and out of its fan in the back leg. The more difficult and expensive-to-build circular section favored for pressurized tunnels was unnecessary. Overall, the tunnel measured approximately 48 by 140 feet in plan. Its cross section gradually increased from 6 by 6 feet in the test section to an 18- by 18-foot settling chamber.[120]

A variable-speed, 600-horsepower electric motor housed in a nacelle and driving a single, 14-foot-diameter fan powered the tunnel. This combination delivered a maximum air speed of 250 mph through the test section. Heat introduced by the motor and fan was dissipated through an air exchange tower that continuously exchanged a small fraction of tunnel air for cooler outside air. As with other such towers, its sidewall slots used the changing static pressure of the flowing air to drive the air exchange with no need for auxiliary fans.

The Stability Tunnel's most distinctive feature was its ability to utilize two different, interchangeable, test sections. Both were 36 feet long and had 6- by 6-foot cross sections at each end, but they were otherwise quite different. One maintained the square cross section throughout its length, but its side walls were made flexible and adjustable to generate flows moving in a horizontal arc past the model. Different screens, made up of vertical wires with varying spacing, could be installed at the test section entrance to provide some additional capability to alter the airspeed profile across the model's span. For pitch studies, the model was rolled 90 degrees. Most models were mounted on either a single pylon or three struts. These were bolted to a turntable in the floor that could rotate to change the yaw (or pitch) angle. The second test section induced a rotational swirl to the test section flow. To accomplish this, it transitioned into a 75-inch-diameter circular cross section, where a set of nine radial blades, driven by an external rim drive, rotated to start the swirl, which then passed the model in a helical pattern. Most models used the pylon mounting for swirl tests. The various mounts were attached to the electro-mechanical balance below the floor.

A steel-framed-and-sheathed test chamber approximately 35 feet by 38 feet in plan enclosed the test section, and it furnished the smooth floor and equipment needed to perform test-section changes. This chamber also housed the rather rudimentary controls for the tunnel. Large doors allowed movement of the test sections and models in and out of the chamber as needed.

HISTORY

The Stability Tunnel was an outgrowth of work previously done in other Langley wind tunnels, particularly the free-flight and spin tunnels, regarding airplane stability and controllability. While these tunnels had demonstrated their value in reproducing the dynamic motions of various airplane designs and in devising procedures for resolving many adverse flight situations, such as spins, much remained to be learned and quantified about the effects of flows around an aircraft that were not uniform. While it may seem like an airplane flying through still air—or vice versa, as in a wind tunnel—will experience uniform initial flow conditions all around the airframe, this is rarely the case in the real world, where winds and maneuvers cause the flow to be nonuniform. For an airplane in a turn, for instance, its outboard wing must move through the air slightly faster than its inboard wing, which means differences in lift and control-surface effect. The sharper the turn, the more severe these effects, and they will be affected by banking as well. Similarly, wing tips move through the air faster than wing roots during rolls. By 1940, airplane performance had reached levels where these effects could no longer be neglected, but no wind tunnel existed that could produce the type of nonuniform conditions necessary to them. In fact, one goal of wind tunnel design had always been to make the airflow as uniform and non-turbulent as possible.[121]

To achieve rotational, or swirling, flow, the tunnel's designers[122] designed a test section that transitioned from square to circular and inserted a rotating set of nine radial blades. These blades had a varying pitch angle from root to tip that imparted a helical swirl to the flow. The blade assembly was rim-driven by a small motor outside the tunnel so that the amount of swirl could be adjusted as desired. Models of complete airplanes were generally secured to the balance on a vertical pylon. This arrangement simulated an airplane in a rolling maneuver, such as banking into a turn. As noted above, the tunnel's balance was transitional design that combined mechanical and electrical elements. This may be the only NACA wind tunnel so equipped, as all-electrical strain gages began to dominate wind tunnel force instrumentation during the 1940s.[123]

Simulation of the airflow during steady yawing (or pitching) required reproducing the relative motion and velocity gradient of the airflow across the complete span of the model. This could be achieved by curving the test section around the model, which was accomplished by making the side walls flexible. Manually operated screw jacks set the desired curvature to suit the requirements of each test. This necessitated a square cross section, something incompatible with the circular swirl test section, so the designers decided to make two separate test sections that could be interchanged as needed. Millard J. Bamber has been credited with the curved-wall design, but it is less certain whether he initiated the idea of interchangeable test sections.[124]

Curving the side walls reproduced the arcing flow over the length of a model, making studies and generating the lateral effects on fuselage and tail needed, but that alone did not vary the airspeed across the span. To do that, engineers inserted screens consisting of vertical wires at the test section inlet. The spacing of the wires varied across the face

of the screen, with wires close together on what would be the inside of the curve and gradually spaced farther apart across to the outside. These wires introduced resistance to the flow that tailored the flow, resulting in a relatively linear change in velocity across the test section's width. These screens, with several configurations of wires, were mounted in easily changeable frames. The result was not perfect, but it far exceeded what could be done elsewhere.[125]

Construction of the Stability Tunnel began in 1940, and the tunnel became operational in June 1942. Reports published over the next 15 years indicate that both test sections were used extensively and that new test concepts and mounting hardware expanded the repertoire to include forced- and free-oscillation testing. A number of these tests involved the damping characteristics of swept wings and tails at low speeds, and test results frequently differed from the best theory of the time. Such findings had a direct impact on airplane design during the 1950s.[126]

To perform the forced oscillation tests, the Stability Tunnel team developed a device that would precisely oscillate a model through a set sweep at a given frequency. They also devised a mount that gave the model considerable freedom to oscillate at its natural frequency in the airstream. These techniques could be employed in conventional wind tunnels as well, which opened up possibilities for similar tests at higher speeds and with larger models, ironically making the Stability Tunnel obsolete—in essence, a victim of its own success.

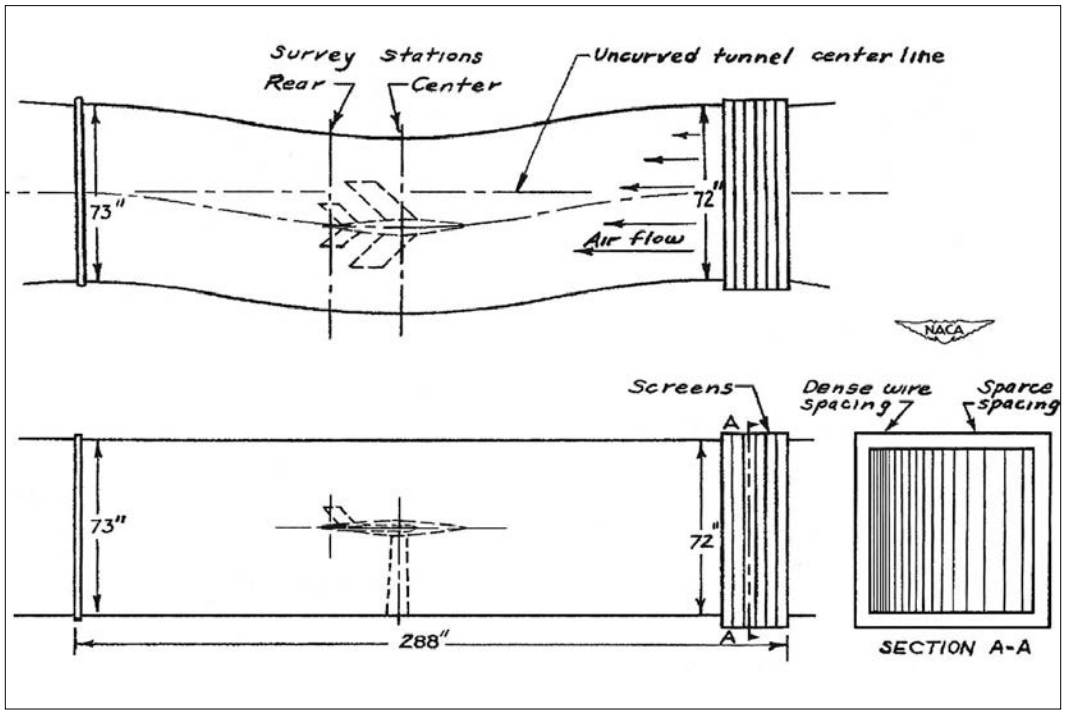
About 1958, the NACA began discussions with the Virginia Polytechnic Institute (now simply Virginia Tech) in Blacksburg, Virginia, about a possible donation of certain wind tunnels to help the school build a stronger academic and research campus. The Stability Tunnel fit well with the school's plans, so it was dismantled, moved, and reerected in Blacksburg during 1958–59. It remains in academic and research service at Virginia Tech. Still referred to as the Stability Tunnel, it has been upgraded with a new, 6- by 4-foot linear test section (others can be inserted), modern instrumentation, and an improved fan for greater operating efficiency. In spite of these changes, the tunnel looks much like it did when at Langley, with the biggest external difference being the style of sheathing on the air exchange tower. The tunnel's test chamber connects to Randolph Hall the same way it interfaced with Building 1149.[127]

At Langley, Building 1149 was not demolished, but converted for other uses. It continues to survive as a base medical facility, and another, newer structure, Building 1153, occupies the area formerly occupied by the tunnel.

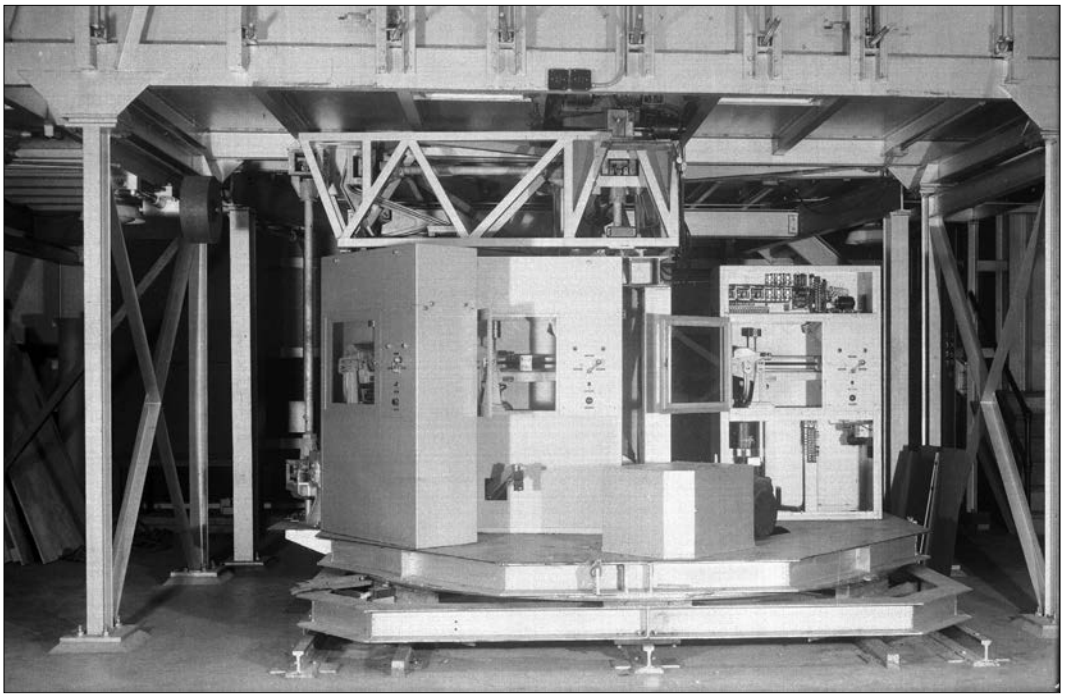
Taken during setup operations in 1943, this view shows the Stability Tunnel's curved test section with its flexible walls set straight. Note the three-strut mount on the turntable, as well as the similar sidewall turntable panel. (Photo credit: NASA LRC-1943-B701_P-32202)

This view from 1947 shows a swept wing on the sidewall mount set up for pitching-flow tests using the Stability Tunnel's curved test section with its sidewalls undeflected. (Photo credit: NASA LRC-1947-B701_P-54913)

This set of blades in the Stability Tunnel's swirl test section rotated to impart a helical swirl to the flow. In this 1952 test, an experimental D-558-2 is being studied for roll behavior as it glides to an unpowered, or "dead stick," landing. (Photo credit: NASA LRC-1952-B701_P-77038)

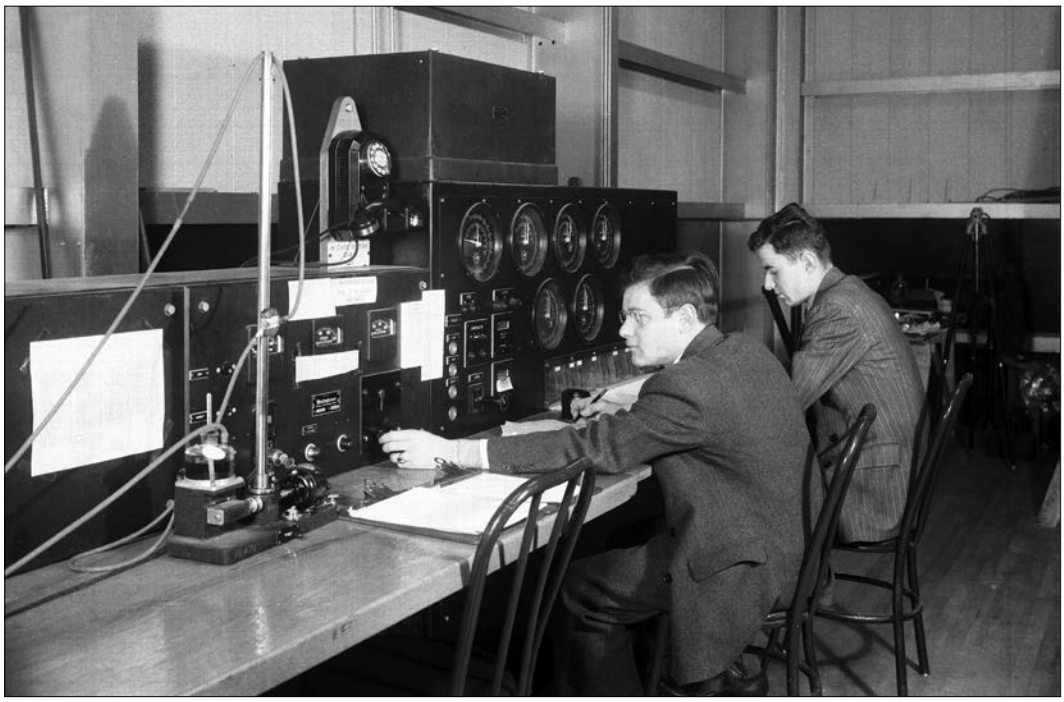


This drawing illustrates the geometry of the Stability Tunnel's curved test section and screens. The lengths of the airflow arrow in the plan view indicate relative velocity across the section's width. (Image credit: NACA TN-2483, Fig. 3)

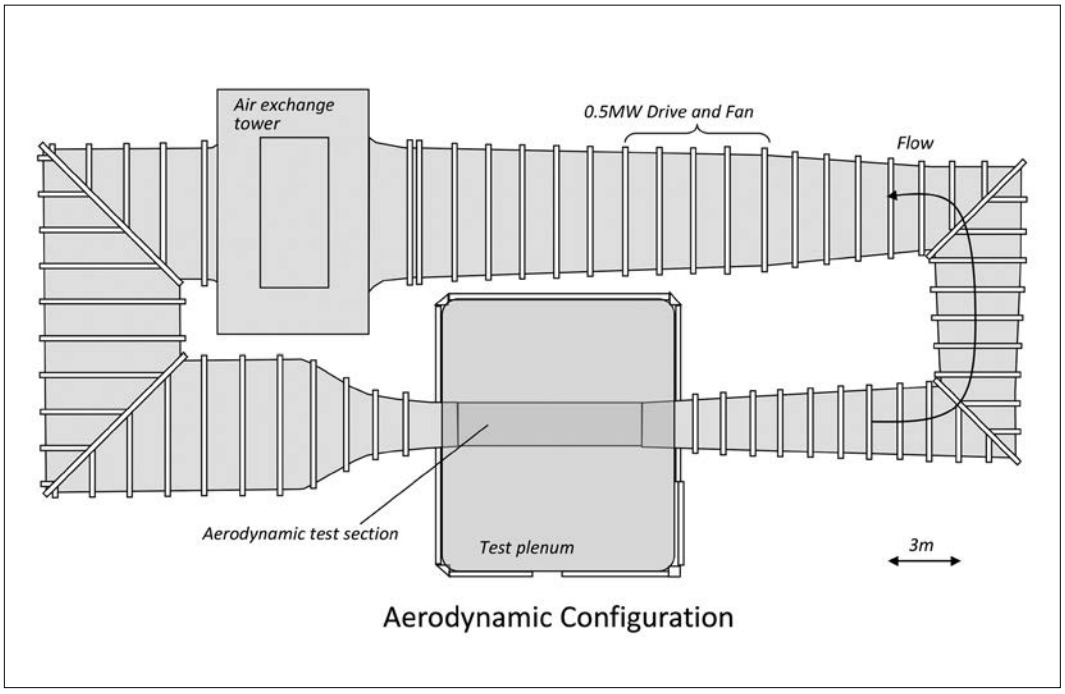


The Stability Tunnel's balance was a transitional instrument that combined mechanical scales with electrical transducers to "read" and transmit the data to the control room. (Photo credit: NASA LRC-1943-B701_P-32201)

Looking upstream through the Stability Tunnel's curved test section in 1947. Note the wire screen at the entrance and the pylon mounted on the floor turntable. (Photo credit: NASA LRC-1947-B701_P-52408)



Two test engineers operating the Stability Tunnel from its rudimentary control panel in 1943. Note the internal steel framing and wooden floor of the test chamber. (Photo credit: NASA LRC-1943-B701_P-32200)



While this plan drawing of the Stability Tunnel at Virginia Tech shows little external change from its appearance while in service at Langley, the original fan blades and test sections have been replaced. (Image credit: Virginia Tech Department of Aerospace and Ocean Engineering)

Top and bottom: The Stability Tunnel as it currently appears next to Randolph Hall at Virginia Tech. (Photo credit: Virginia Tech Department of Aerospace and Ocean Engineering)

9-INCH SUPERSONIC TUNNEL

This general view of the 9-Inch Supersonic Tunnel in 1946 shows the tunnel and its control console. Note the circular test section windows and the rolling gantry that supported the schlieren system. (Photo credit: NASA LRC-1946-B701_P-47555)

SIGNIFICANCE

The 9-Inch Supersonic Tunnel (9-Inch SWT) was Langley's first wind tunnel capable of producing supersonic speeds continuously, and it served as the NACA's primary supersonic research tool during the World War II years. According to Langley researcher John Becker, "This pioneering little tunnel provided timely education and experience for the NACA in the 1941–1945 period immediately preceding the major drive for large supersonic tunnels."[128]

DESCRIPTION

Originally named the Model Supersonic Tunnel, the 9-Inch SWT occupied Building 1191 in Langley's West Area. Though the tunnel was initially built as an open-circuit fabricated from steel plate and structural sections, engineers rebuilt it with a closed circuit within three years of its opening. The open-circuit tunnel utilized an axial-flow compressor driven by a 1,000-horsepower, variable-speed electric motor. For the closed-circuit design, the engineers increased the power to 3,500 horsepower and added a desiccant air dryer. As its name indicates, it featured a 9- by 9-inch test section. Two distortion-free circular windows were fitted to each side to facilitate schlieren photography. One pair was mounted on separable hinges for easy opening or removal for model and sting access. The sting included a three-component balance system. The

9-Inch SWT's diffuser, although square in cross section, included a circular expansion joint at its midpoint.[129]

An early reference to the 9-Inch SWT indicates the tunnel was initially equipped with an adjustable nozzle, but this apparently was not successful. Later technical notes and reports with brief descriptions of the tunnel specify it as having interchangeable nozzle blocks for different Mach numbers.[130]

The 9-Inch SWT was originally built with schlieren equipment. Since rigidity and an ability to hold precision adjustments in place were essential for high-quality schlieren photographs, the various mirrors, lenses, and camera mounts were installed on a gantry that straddled the tunnel. Technicians manually rolled the gantry into and out of position along a track in the floor.

By 1955, the 9-Inch SWT had acquired a shielded sting that reduced its drag. About this same time, the test section walls were modified to incorporate larger access doors, and two oval windows replaced the four circular ones.

In 1958, the Virginia Polytechnic Institute acquired the 9-Inch SWT, sans drive, from the NACA and moved it from Langley to its campus in Blacksburg, Virginia. The school bought only the tunnel's core components since it planned to reerect the tunnel as a blowdown tunnel. Installed on the ground floor of Randolph Hall, the tunnel has much of its original appearance at Langley, though its airflow control valve has been changed, and the schlieren apparatus is mounted on several stands instead of a large gantry. Three interchangeable nozzle blocks are available for Mach numbers 2.4, 3.0, and 4.0. The tunnel's control panel, which the school first installed next to the tunnel, has been replaced by a computerized panel in an adjacent room. Instrumentation and data acquisition systems have been modernized over the years as well.[131]

HISTORY

The origin of the 9-Inch Supersonic Tunnel is one of many Langley stories that involve a bit of intrigue and even subterfuge. In spite of the dramatic changes occurring during the design revolution of the 1930s, the NACA's main committee maintained a healthy skepticism regarding supersonics, seriously doubting that supersonic flight was even possible, much less desirable. Nevertheless, when Eastman Jacobs received an invitation to present a paper at the Fifth Volta Conference on High-Speed Aeronautics in 1935, the NACA supported his trip to Rome for it. At the conference, Jacobs learned much about the European efforts in supersonic research, including a supersonic wind tunnel at Guidonia, Italy, and he returned enthusiastic about starting similar work at Langley. Both he and Theodore von Kármán, one of the most influential aeronautical theorists of the time, urged the U.S. Army and the NACA to build supersonic facilities, but neither initially responded.

Not easily deterred, Jacobs assigned a recently hired physicist, Arthur Kantrowitz, to study the matter further, and the two men concluded that supersonic flight was possible. In one of Langley's notable examples of "bootlegging," Jacobs assigned Kantrowitz the

task of designing a small supersonic tunnel about 1937. Assisted by engineers in the section, he completed the design within a year and a half.[132]

Whether Langley began fabricating parts for the tunnel before receiving approval from NACA headquarters is unclear, but authorization ultimately came for what the main committee saw as a pilot model for a larger supersonic tunnel to be built at the new Ames Laboratory in California.[133]

The 9-Inch SWT opened in mid-1942. It achieved supersonic speeds, but two problems immediately appeared. Kantrowitz had designed the little tunnel with an adjustable nozzle and a variable-speed compressor to provide some degree of speed control, but neither of these ideas proved to be successful. The team soon replaced the adjustable nozzle with a fixed one designed for Mach 2.4. By 1951, additional nozzles designed for Mach 1.6 and 1.9 were available that would interchange with the original one, along with 11 screens in the settling chamber to reduce turbulence.[134]

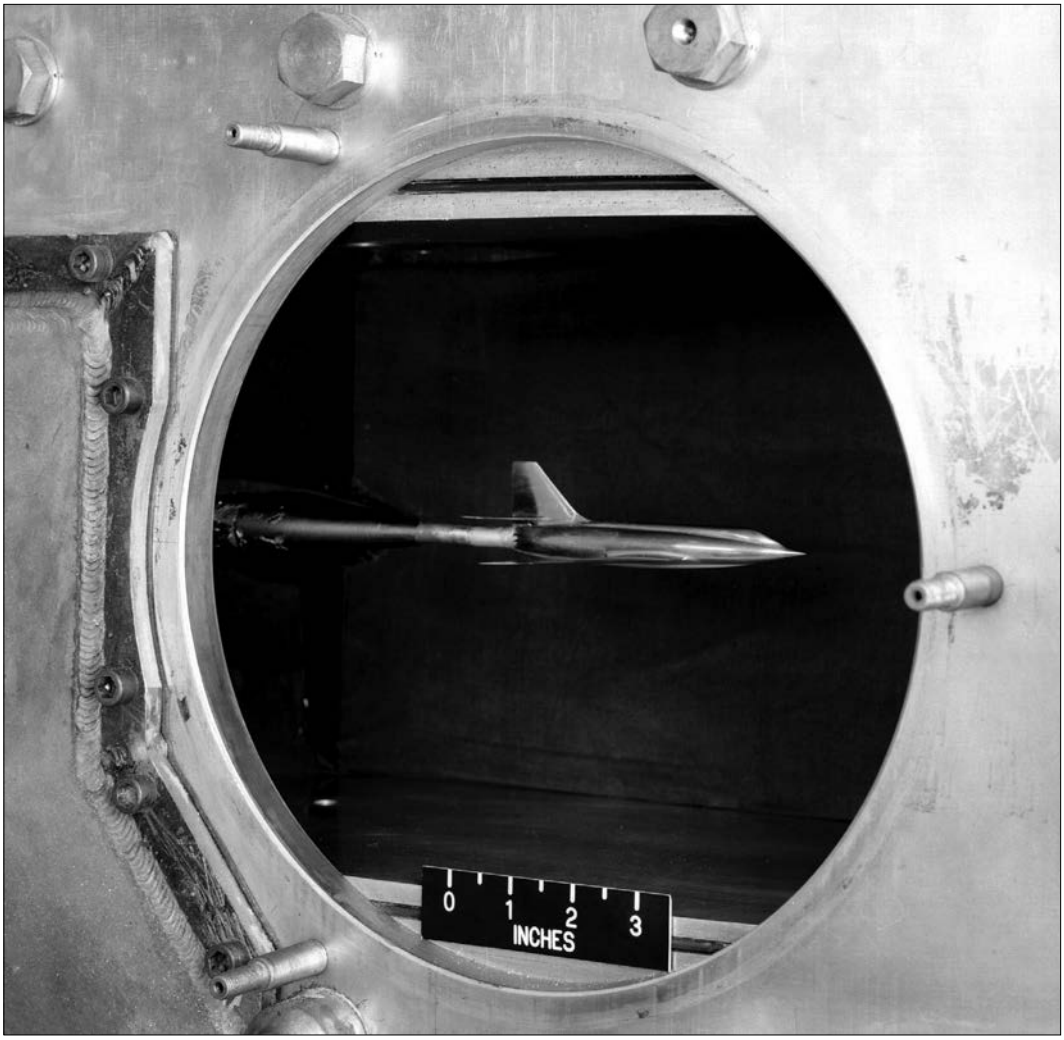
The second problem required a significant rebuilding of the tunnel to solve. The open-circuit tunnel was plagued with condensation, thanks to Langley's humid environment and the pressure and temperature drops from the nozzle's throat through the test section. Such condensation is very detrimental to test accuracy, and it can damage models as well. The only solution was to add a desiccant dryer to dehumidify the air to a low dew point. To retain the dry air, the engineers converted the tunnel into a closed circuit during 1944–45. The core part of the tunnel did not change. It is not clear if they tried to operate in closed mode with the same motor and compressor, but historian James Hansen reported that the tunnel was repowered to 3,500 horsepower—clearly necessary for higher Mach numbers—in 1946.[135]

Intended as a pilot tunnel, the 9-Inch SWT also demonstrated its own value as a research tool, a role it performed at Langley for more than a decade. Test projects during the 1950s largely involved force-and-moment investigations of supersonic wings, and several of these involved designs for missiles, particularly missiles with tandem wings. The reports of these tests indicate test speeds of approximately Mach 1.6, 1.9, and 2.4.[136]

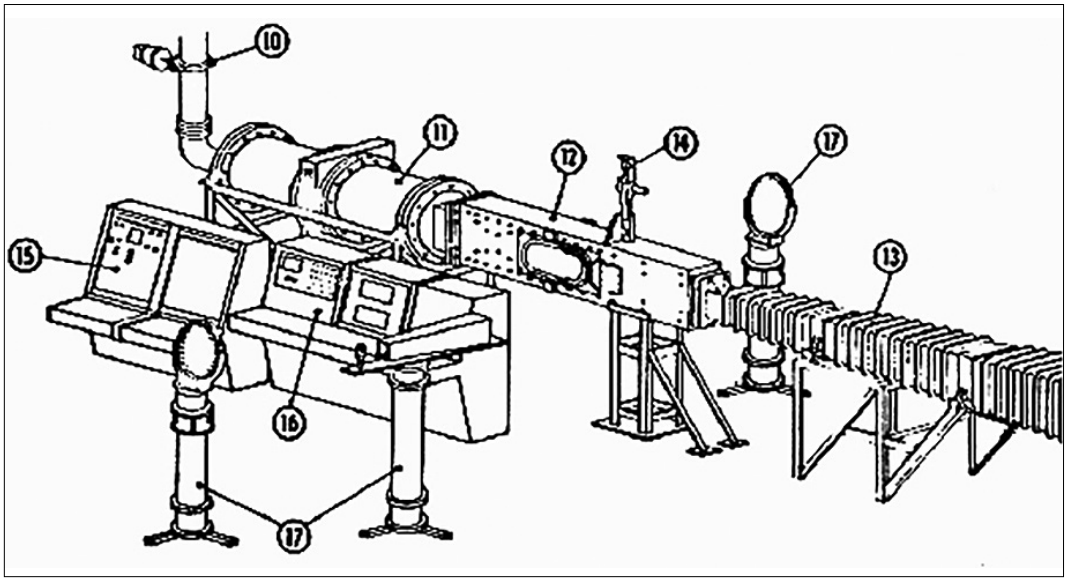
By 1958, a number of other supersonic tunnels were in service at the NACA's Langley, Ames, and Lewis laboratories, not to mention additional ones operated by universities and aircraft manufacturers. Most were larger and more capable than the 9-Inch SWT, so Langley chose to decommission it. At the time, the Virginia Polytechnic Institute in Blacksburg, Virginia, had recently completed an aeronautical engineering building and looked to add some wind tunnels to support its academic program and help expand a research program. The school ultimately acquired three tunnels from Langley, including the 9-Inch SWT in 1958. Virginia Tech decided to operate the tunnel in blowdown mode from a compressed-air system it acquired elsewhere, so it did not need Langley's drive or return duct. The school installed the tunnel on the ground floor of Randolph Hall and began operating it in 1963. A subsequent donation of a larger compressor shortened turnaround times to about 20 minutes following a 15-second run.

Since opening the tunnel, Virginia Tech has kept it busy with a variety of research work. Since 1963, the school has installed several upgrades to its instrumentation and data-acquisition systems, as well as an improved flow-control valve ahead of the settling chamber. It now uses interchangeable nozzles designed for Mach 2.4, 3.0, and 4.0. Though the college did not take the schlieren gantry, it assembled its own schlieren system that sees frequent use. When originally installed in Randolph Hall, the tunnel's control console was located close to it, as it had been at Langley. As computerized instrumentation and control systems replaced the manual devices, these were relocated to an adjacent room.[137]

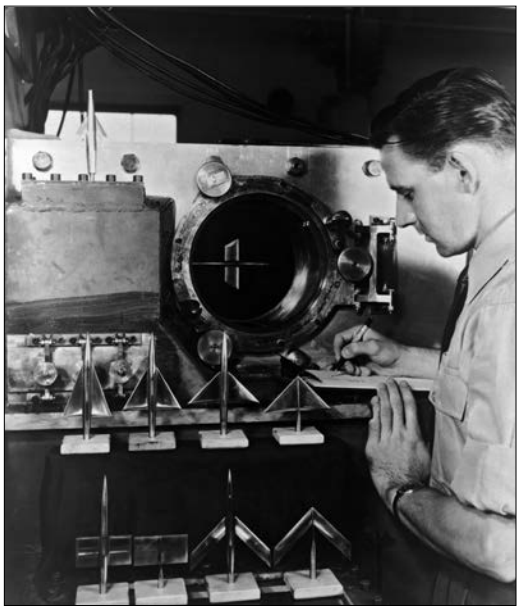
This tunnel, now known simply as the Supersonic Tunnel, remains in active service, and Virginia Tech's Department of Aeronautical and Ocean Engineering expects to operate it well into the future.



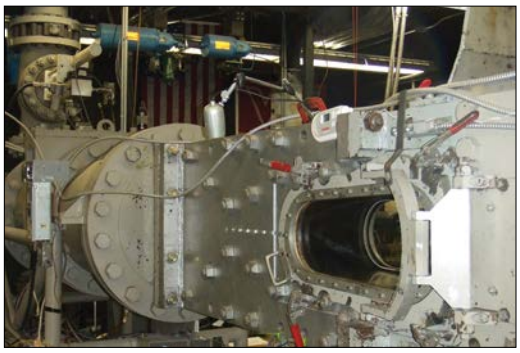
This 3-inch-long X-2, seen here in 1947, is typical of the models tested in the 9-Inch SWT. (Photo credit: NASA LRC-1947-B701_P-53780)



This drawing depicts the 9-Inch Supersonic Tunnel as installed at Virginia Tech, where it supports both educational and research activities. The school acquired the core portions of the tunnel from the NACA in 1958, but without Langley's drive system. Virginia Tech installed the tunnel to run in blowdown mode exhausting to the atmosphere. While the core portions of the tunnel remain largely as they were at Langley, much of the instrumentation, control, and ancillary equipment has been improved, and the control panel has been moved to an adjacent room. (Image credit: Virginia Tech Department of Aerospace and Ocean Engineering)



Researcher James Mueller looks into the 9-Inch Supersonic Tunnel's test section at a model in 1946. Note the nozzle throat visible through the window over his shoulder. (Photo credit: NASA LRC-1946-B701_P-50193)



The 9-Inch Supersonic Tunnel continues to support both academic and research work at Virginia Tech in Blacksburg, Virginia. (Photo credit: Virginia Tech Department of Aerospace and Ocean Engineering)

7- BY 10-FOOT LOW-SPEED WIND TUNNEL

This 1950 aerial view shows the Low-Speed (L) and High-Speed (R) 7- by 10-Foot Wind Tunnels surrounding the central office and shop building. Though similar in appearance, less power gave the low-speed tunnel a maximum speed about one-half that of its sibling. (Photo credit: NASA LRC-1950-B701_P-67616)

SIGNIFICANCE

The 7- by 10-Foot Low-Speed Wind Tunnel, also known as the 300-Mile-per-Hour 7- by 10-Foot Tunnel, was not built to advance the state of the art in wind tunnel design, but rather to reduce the growing backlog of work during World War II in Langley's 1930-vintage 7- by 10-Foot AWT. Accordingly, its primary significance derives not from any technological advance, but in the recognition by NACA engineers and managers that this size and speed were eminently practical for a wide variety of test subjects and programs and their incorporation of almost all proven wind-tunnel technologies of the time. While not outstanding or unique in its capabilities, this versatile tunnel marked the point where the subsonic wind tunnel passed beyond maturity and into the realm of reliable productivity to meet demanding schedules.

The addition of a 17- by 17-foot test section in 1956 made this tunnel the first to feature dual, tandem test sections for two speed ranges. This concept, later adopted in a

few other tunnels, increased the tunnel's usefulness and gave researchers an early facility in which to study vertical/short take-off and landing (V/STOL) aircraft.

DESCRIPTION

The 7- by 10-Foot Low-Speed Wind Tunnel (7- by 10-Foot LSWT) was the second wind tunnel built in Langley's West Area. Together with a similar, but more-powerful, 7- by 10-Foot High-Speed Wind Tunnel and central support structure, it was erected about ¼ mile west of the 16-Foot High-Speed Tunnel. This complex became Building 1212, with the 7- by 10-Foot LSWT being the 1212-A section on the south side.

Although the 7- by 10-Foot LSWT did not break any new ground in wind tunnel design, it nevertheless benefited from the preceding developments and entered service in February 1945 as a fully modern facility. By the time of its authorization in 1942, all of the critical design elements were in place and proven, including the closed circuit and test section with a single-return duct, an externally braced steel shell, a variable-speed electric motor driving an airfoil-bladed fan, an air-exchange tower for temperature control, a six-component balance, and multitube manometers for pressure measurements around the test model. All of these elements were incorporated into the 7- by 10-Foot LSWT.

Designed as an atmospheric tunnel, the 7- by 10-Foot LSWT employed a rectangular cross section throughout its circuit, except for transitions into and out of its fan. Without pressurization, the more difficult and expensive-to-build circular section was unnecessary. Overall, the tunnel measured approximately 75 by 210 feet in plan. Its cross section gradually increased from 7 by 10 feet in the test section to a 30- by 30-foot settling chamber.[138]

A variable-speed, 1,600-horsepower electric motor driving a single, 25-foot-diameter fan powered the tunnel. The motor was enclosed in a nacelle upstream from the fan. This combination provided a 0–300-mph speed range in the test section. Countervanes immediately after the fan eliminated any swirl induced by the fan. Heat introduced by the motor and fan was dissipated through an air exchange tower that continuously exchanged a small fraction of tunnel air for cooler outside air. Identified on one drawing as a "ventilating tower," its sidewall slots used the changing static pressure of the flowing air to drive the air exchange, without a need for auxiliary fans.

To facilitate rapid model changes, the tunnel's shop area was built at the same elevation as its test section, enabling the assembly of models on carts that could be rolled directly into the test section. Full models were mounted on stings or vertical struts, and sidewall mountings accommodated semi-span airfoils.[139]

After 1956, the 7- by 10-Foot LSWT featured a second test section, making it the first wind tunnel to have dual, tandem test sections. New wall sections formed a 15.8-foot-high by 17-foot-wide test section in a portion of the settling chamber immediately downstream of Turn 4. Airflow through this larger test section reached a maximum speed of 80 mph, and speed control was very precise over the full speed range, making

it well suited for the study of V/STOL aircraft during their critical take-off and landing maneuvers. Since the same fan, drive, and return circuit were used for both test sections, and air always flowed through both of them, test measurements could be taken in only one at a time.[140]

HISTORY

The 7- by 10-Foot Low-Speed Wind Tunnel was born out of necessity. The NACA's 7- by 10-Foot AWT had been the setting for a variety of test programs since its opening in 1930, and its size had proven to be a very practical one that matched the general height-to-width proportions of monoplanes well. Clearances in both directions allowed for investigations involving vertical and lateral forces without undue wall effects, and its six-component balance measured forces and moments along and about an airplane's three axes, giving engineers comprehensive sets of data. As aircraft speed increased rapidly throughout the 1930s, the tunnel's 80-mile-per-hour top speed began to limit tests to takeoff and landing performance. Accordingly, the 7- by 10-Foot AWT saw several systematic investigations of high-lift devices and systems, many of which focused on the plane's stability and control characteristics with such devices deployed. At least 50 different aircraft models benefited from testing in the tunnel.[141]

The threat of World War II further increased the number and developmental pace of new military aircraft. Since most of these designs were pushing the new technologies developed during the 1930s, the demand for test time in wind tunnels ballooned, pushing Langley's capabilities to the limit. Rear Admiral Arthur Cook and Captain Walter Diehl of the navy's Bureau of Aeronautics had been studying the growing problem since 1936 as part of the bureau's Special Committee on Future Research Facilities. In December 1938, the committee recommended that the NACA launch a major expansion effort, to include a second aeronautical laboratory and several new facilities at Langley, and a modern replacement for the 7- by 10-Foot AWT. Already aware of the need, as well as the cost, the NACA used the committee's report to justify a request for funds to Congress. It took almost three years and America's entry into the war, but Congress finally approved funds to build not one, but two new 7- by 10-foot tunnels. One would have sufficient power to approach the speed of sound, but the first to be built would be somewhat more modest in scope, limited to about 300 mph to enable efficient, low-cost testing in a speed range vital to virtually all aircraft.[142]

Langley engineers Thomas A. Harris and Charles J. Donlan led the design team. Their goal was to design and build a basic tunnel that incorporated all elements of tunnel design that had been proven effective and reliable during the previous decade. The result was a utilitarian tunnel with a conservative speed range that would be suitable for a wide variety of unglamorous, but nevertheless essential, tests. Construction began late in 1943, and the tunnel went into service in February 1945. While this was too late to have a major impact on World War II, the new tunnel went online just in time to host a series of test programs involving the low-speed stability of jet aircraft, especially

those with swept wings. The majority of wing tests used semi-span models between 4 and 6 feet long mounted on the balance through the tunnel's sidewall. At the time, American designers knew very little about swept wings, first envisioned by Germany's Adolph Busemann in 1935, and these tests furnished vital data that informed America's first swept-wing planes.[143]

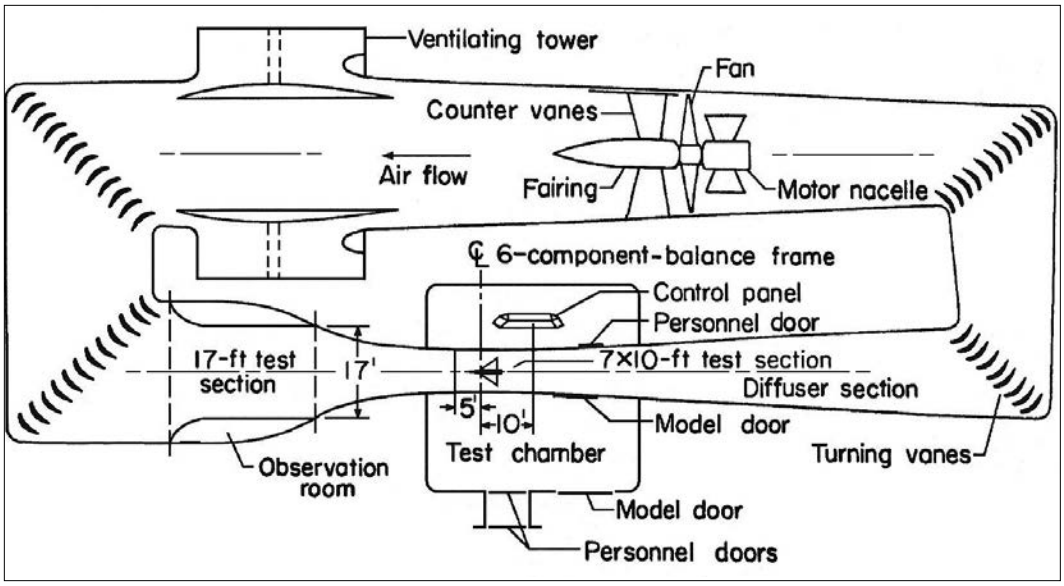
Since the 7- by 10-Foot LSWT was an atmospheric tunnel with a closed test chamber, the moving air induced a partial vacuum on the chamber. This pressure differential served as the prime mover for a 10- by 14-inch induced-draft tunnel that engineers built by the end of 1945. They used this tunnel to develop the throat design for the 7- by 10-Foot HSWT under construction next door. Subsequently, researchers used this little tunnel to develop the first "transonic bump" they then installed in the high-speed tunnel to perform early transonic research. Its final disposition is unknown.[144]

Interest in airplanes that could take off and land vertically, or at least with very short runs, intensified during the 1950s, and a number of jet- and propeller-driven V/STOL concepts were tried. In-flight experience quickly showed the transition from hovering to level flight and vice versa to be a difficult and dangerous affair, so engineers looked to see if wind tunnel testing could be a practical and safer tool. At Langley, engineers looked at modifying an existing wind tunnel for the task, and they decided to install a second test section in the 7- by 10-Foot LSWT's settling chamber. There was room for a rectangular section 15.8 feet high and 17 feet wide, a cross section that would have a speed range of 0–80 mph using the tunnel's existing drive. The size was large enough to accommodate powered models with spans of up to 8 feet. A turntable in the floor provided ±180 degrees of sideslip adjustment, and sting mounts on this allowed for ±30-degree angle-of-attack variation. Used in conjunction with airspeed changes, these adjustments could simulate the transition regime for many proposed designs. Since the tunnel's control remained at its original console, good communication between the operator and test personnel adjacent to the new test section was crucial. By the time of this installation, electric strain gages had become the primary instruments for force and moment measurement, negating any need for a massive mechanical balance like the one installed under the original test section. Tests could be run in only one test section at a time, but separate test models for different programs were routinely installed simultaneously in both sections. To maximize productivity, the day shift ran tests for one program, and the night shift for the other.[145]

The 7- by 10-Foot LSWT ceased operation in May 1970. During its last decade of life, this tunnel demonstrated the continuing value of low-speed testing for V/STOL aircraft, helicopters, and conventional airplanes as well, all of which must fly safely through takeoff and landing maneuvers at low speeds. The success and usefulness of the 17-foot test section fostered the development of a larger tunnel designed solely for that role, a process that resulted in the 14- by 22-Foot V/STOL Transition Research Tunnel. The new tunnel was built just south of the 7- by 10-Foot LSWT, which remained in service during the construction, but it closed soon after the 14- by 22-foot tunnel

entered service. The 7- by 10-Foot LSWT remained in place for several more years, but it was demolished around 1983 to provide room for an expansion of the 14- by 22-foot tunnel's model preparation area. No portion of it is known to have survived.

The 7- by 10-Foot Low-Speed Wind Tunnel's control console and balance scales were grouped together inside its test chamber. In this 1953 image, Hazel Redding and Billie Walker operate the tunnel and record data at the tunnel's control console. (Photo credit: NASA LRC-1953-B701_P-80438)



This drawing shows the arrangement of the 7- by 10-Foot Low-Speed Wind Tunnel after the 1956 addition of the 15.8- by 17-foot test section in the settling chamber. The success of this addition ultimately led to the replacement of this tunnel with the 14- by 22-Foot V/STOL Transition Research Wind Tunnel. (Image credit: NASA drawing)

The six-component balance of the 7- by 10-Foot Low-Speed Wind Tunnel, seen here installed directly beneath the test section in 1945, was similar to its predecessors at Langley. (Photo credit: NASA LRC-1945-B701_P-43762)

Low-speed performance was a serious concern for the designers of early jets. A model F-84, one of America's early jet fighters, is shown here ready for testing in the 7- by 10-Foot Low-Speed Wind Tunnel about 1945. This twin-strut mount was typically used for complete models. (Photo credit: NASA LRC-1945-B701_P-45262)

This unusual view from 1957 looks through both test sections of the modified 7- by 10-Foot Low-Speed Wind Tunnel, with the 15.8- by 17-foot test section in the center and the original 7- by 10-foot test section in the distance. (Photo credit: NASA LRC-1957-B701_P-01191)

The speed range of the 7- by 10-Foot Low-Speed Wind Tunnel was ideal for evaluating the Mercury capsule escape system, as shown in this 1959 test. (Photo credit: NASA LRC-1959-B701_P-03397)

One unusual test in the 7- by 10-Foot Low-Speed Wind Tunnel evaluated the performance of this combination anemometer and wind-direction indicator in 1953. (Photo credit: NASA LRC-1953-B7014_P-81375)

7- BY 10-FOOT HIGH-SPEED WIND TUNNEL

This 1981 aerial view shows the 7- by 10-Foot High-Speed Wind Tunnel's final configuration. Its test section was in the cubical enclosure under the round auxiliary air removal duct. (Photo credit: NASA LRC-1981-B701_P-10677)

SIGNIFICANCE

The Building 1212 complex, which included the 7- by 10-Foot High-Speed Wind Tunnel (HSWT) and its cousin, the 7- by 10-Foot Low-Speed Wind Tunnel (LSWT), was built primarily to reduce the growing backlog of work during World War II in Langley's 1930-vintage 7- by 10-Foot Atmospheric Wind Tunnel. But where the low-speed tunnel furnished additional capacity for testing in the 0- to 300-mile-per-hour range, the high-speed tunnel received additional power and some design refinements that allowed it to have a maximum speed approximately twice that of its counterpart. While these refinements were not introduced in this tunnel, their inclusion in a 7- by 10-foot tunnel illustrated how Langley engineers were making practical, cost-effective trade-offs in wind tunnel design. A few other very large wind tunnels would be built over the next 15 years, but this tunnel proved that, when equipped with most proven features, wind tunnels of about this size were eminently practical for a wide variety of test subjects and programs.

While these unheralded virtues may have been the more important achievements in regard to the evolution of wind tunnel design, the 7- by 10-Foot HST is best known for a research technique pioneered in it: the "transonic bump." Prior to the invention of slotted-wall test sections, stable transonic speeds (i.e., roughly Mach 0.7–1.2) were impossible to maintain in wind tunnels without choking effects. The transonic bump, a

concept transferred from an airplane wing into this tunnel, produced localized airflow in the transonic range and permitted useful testing of small models.

Even after slotted-wall tunnels captured the transonic work, this tunnel remained one of Langley's workhorse tunnels for almost 50 years.

DESCRIPTION

The 7- by 10-Foot HSWT was the third wind tunnel built in Langley's West Area. Together with a similar, but less powerful, 7- by 10-Foot LSWT and central support structure, it was erected about a quarter mile west of the 16-Foot HST. This complex became Building 1212, with the 7- by 10-Foot HSWT being the 1212-B section on the north side.

Although the 7- by 10-Foot HSWT broke little new ground in wind tunnel design, it nevertheless benefited from the preceding developments and entered service in November 1945 as a fully modern facility. By the time of its authorization in 1943, all of the critical design elements were in place and proven, including the closed circuit and test section with a single-return duct, an externally braced steel shell, a variable-speed electric motor driving an airfoil-bladed fan, air-exchange for temperature control, a six-component balance, and multitube manometers for pressure measurements around the test model. All these elements were incorporated into the 7- by 10-Foot HSWT.

Designed as an atmospheric tunnel, the 7- by 10-Foot HSWT employed a rectangular cross section throughout its circuit, except for transitions into and out of its fan. Without pressurization, the more difficult- and expensive-to-build circular section was unnecessary. Overall, the tunnel measured approximately 78 by 242 feet in plan. Its cross section gradually increased through the circuit, from 6 feet, 7 inches wide by 9 feet, 7 inches high in the test section to a 32- by 32-foot settling chamber.[146]

A variable-speed, 14,000-horsepower electric motor driving a single, 25-foot-diameter fan powered the tunnel. The motor was enclosed in a nacelle upstream from the fan. This combination provided a 0- to 675-mile-per-hour speed range in the test section. Countervanes immediately after the fan eliminated any swirl induced by the fan. Heat introduced by the motor and fan was dissipated through air exchange towers that continuously exchanged a small fraction of tunnel air for cooler outside air. Unlike earlier designs that used a single tower, the tunnel had an exhaust tower downstream from the fan and a separate intake tower just downstream from the test section, making it the NACA's first tunnel to split these functions. Together, their operation was similar to a single exchange tower, using the changing static pressure of the flowing air to drive the air exchange without a need for auxiliary fans.

To facilitate rapid model changes, the tunnels' shop area was built at the same elevation as its test section, enabling the assembly of models on carts that could be rolled directly into the test section. Full models were mounted on stings or vertical struts, and side-wall mountings accommodated semi-span airfoils.

HISTORY

Building 1212 and its two 7- by 10-Foot wind tunnels were born out of necessity. The NACA's 7- by 10-Foot AWT had been the setting for a variety of test programs since its opening in 1930, and its size had proven to be a very practical one that matched the general height-to-width proportions of monoplanes well. Clearances in both directions allowed for investigations involving vertical and lateral forces without undue wall effects, and its six-component balance measured forces and moments along and about an airplane's three axes, giving engineers comprehensive sets of data. As aircraft speed increased rapidly throughout the 1930s, the tunnel's 80-mile-per-hour top speed began to limit tests to takeoff and landing performance. Accordingly, the 7- by 10-Foot AWT saw several systematic investigations of high-lift devices and systems, many of which focused on the plane's stability and control characteristics with such devices deployed. At least 50 different aircraft models benefited from testing in the tunnel.[147]

The threat of World War II further increased the number and developmental pace of new military aircraft. Since most of these designs were pushing the new technologies developed during the 1930s, the demand for test time in wind tunnels ballooned, pushing Langley's capabilities to the limit. Rear Admiral Arthur Cook and Captain Walter Diehl of the Navy's Bureau of Aeronautics had been studying the growing problem since 1936 as part of the bureau's Special Committee on Future Research Facilities. In December 1938, the committee recommended that the NACA launch a major expansion effort, to include a second aeronautical laboratory and several new facilities at Langley, as well as a modern replacement for the 7- by 10-Foot AWT. Already aware of the need, as well as the cost, the NACA used the committee's report to justify a request for funds to Congress. It took almost three years and America's entry into the war, but Congress finally approved funds to build not one, but two new 7- by 10-foot tunnels. One would be limited to about 300 mph, but the second one, the 7- by 10-Foot HSWT, would have sufficient power to approach the speed of sound.[148]

Langley engineers Thomas A. Harris and Charles J. Donlan led the design team for both tunnels. Their goal for the 7- by 10-Foot HSWT was to design and build a basic tunnel that incorporated all elements of tunnel design that had been proven effective and reliable during the previous decade, but with the additional power and speed needed to better the performance expected from airplanes under development. The result was a utilitarian tunnel with the ability to efficiently reach about Mach 0.9. Construction began late in 1943, and the tunnel went into service in November 1945. While this was too late to have any impact on World War II, the new tunnel was suddenly thrust into the spotlight as one of the few wind tunnels capable of generating test conditions suitable for the new jet airplanes, particularly those with swept wings. At the time, American designers knew very little about swept wings, first envisioned by Germany's Adolph Busemann in 1935, and tests in the 7- by 10-Foot HSWT furnished critical data for American designers.[149]

Before Langley's Ray Wright developed a practical slotted-wall test section that yielded stable transonic operation, as discussed under the 8-Foot HST, the only available test methods involved actual flight. One method involved dropping instrumented models from airplanes, where falling models usually experienced only a few seconds of transonic flight as they accelerated through the region. The other took advantage of the localized region of sonic flow that could be produced above the wing of a modern fighter at high-subsonic speed. Small models mounted on top of the wing, usually half models, experienced sonic flow during high-speed dives. This was more controlled than drop testing, but still limited in duration and somewhat risky. As the 7- by 10-Foot HSWT was nearing completion in 1945, engineers reasoned that this concept might be transferred to the new tunnel. Using a 10- by 14-inch induction tunnel powered by the 7- by 10-Foot LSWT's differential pressure, they developed an airfoil-shaped "transonic bump" that was then mounted on the floor of the 7- by 10-Foot HSWT. As with the wing-flow tests, localized flow reached Mach 1 as the tunnel approached its 675-mile-per-hour top speed. Because the localized region was small and the tunnel's speed otherwise subsonic, it did not choke. Small models, both half models and sting-mounted full models, on or near the bump experienced Mach 1 flow and yielded some of the earliest reliable data about the transonic regime. At least two different bump designs were used well into the 1950s.[150]

In 1953, the tunnel gained true transonic capability with the installation of a slotted wall test section, which raised its maximum speed to Mach 1 without the bump. That capability was supplemented a couple of years later. The installation of a massive, 35,000-horsepower air removal system at the 16-Foot Transonic Tunnel proved test section air extraction to be a useful way of increasing a transonic tunnel's speed. Since that facility was only about a quarter mile away and the compressor not used full-time, connecting the 7- by 10-Foot HSWT to it increased its speed range up to Mach 1.2 easily and economically.[151]

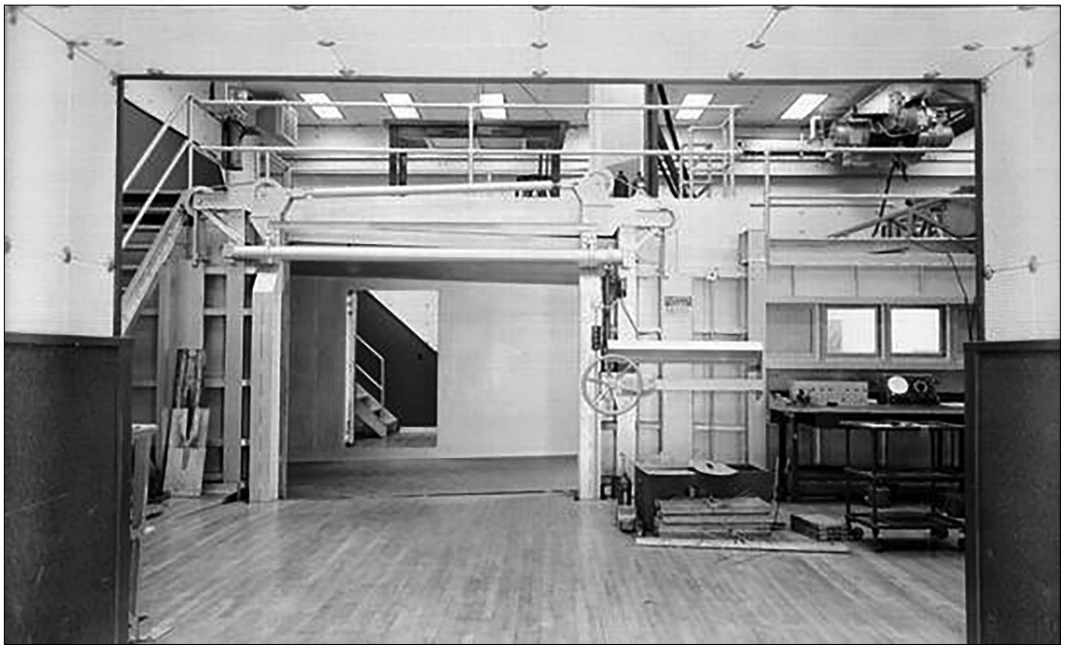
As was the case with its slower sibling, the 7- by 10-Foot HSWT proved to be a workhorse at Langley, and it hosted a wide variety of test programs. Many of the early ones used the transonic bump capability to investigate every conceivable aspect of swept-wing aerodynamics, and papers emerged almost monthly. By 1955, the volume was such that the NACA even published a technical note to summarize just the studies of plan form on lift and drag.[152]

While the tunnel continued to host a wide variety of tests to evaluate the aerodynamic characteristics of wings, programs involving complete airplanes and multi-component configurations found the 7- by 10-Foot HSWT suitable as well. One of its last programs under NACA management investigated how the B-52/X-15 combination worked, especially during the X-15's release from under the bomber's wing. Almost 20 years later, somewhat similar tests for NASA examined the Space Shuttle Orbiter/747 combination.[153]

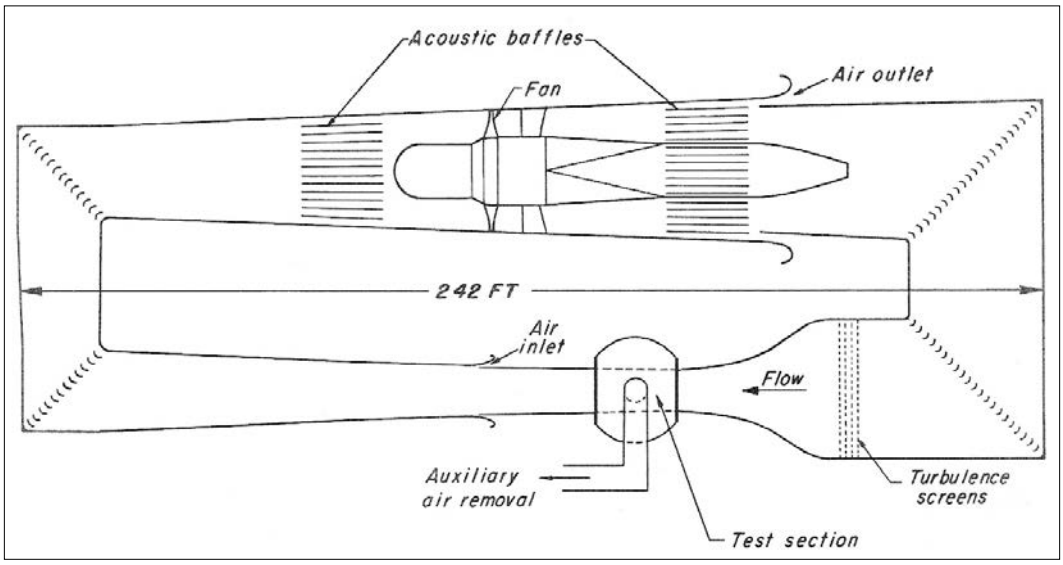
Most wind tunnels see model breakage and component failures from time to time. Even with rigorous safety programs, some risk is inherent with research into unknown

realms. But on 9 July 1985, the 7- by 10-Foot HSWT experienced an unusual, and unusually harrowing, event when its fan suddenly shattered while spinning at 465 revolutions per minute, or 90 percent of its maximum speed. The event resulted in the catastrophic failure of all 18 Sitka spruce blades and bent the main drive shaft as well. The wooden blades, which had been in service for 10 years without any problems, were a common design used in many tunnels, and Langley initiated a thorough investigation of the failure. After the analysis indicated that the failure of a single blade had caused the accident, and that no systemic problem existed with the drive, Langley spent $1.7 million to repair the tunnel with no major design changes.[154]

The repaired 7- by 10-Foot HSWT continued to host test programs until being closed in 1993, a victim of NASA's budget priorities, but it was maintained in serviceable condition for more than a decade. Thanks to its combination of size, speed, and relatively low operating cost, the tunnel did see some new test programs after 1993, including a set of high-angle-of-attack studies that employed a roughened fuselage to better simulate boundary-layer characteristics. In spite of its continued ability to support advanced research, budgetary constraints ultimately forced the 7- by 10-Foot HSWT's permanent closure, and it was demolished late in 2008.[155]

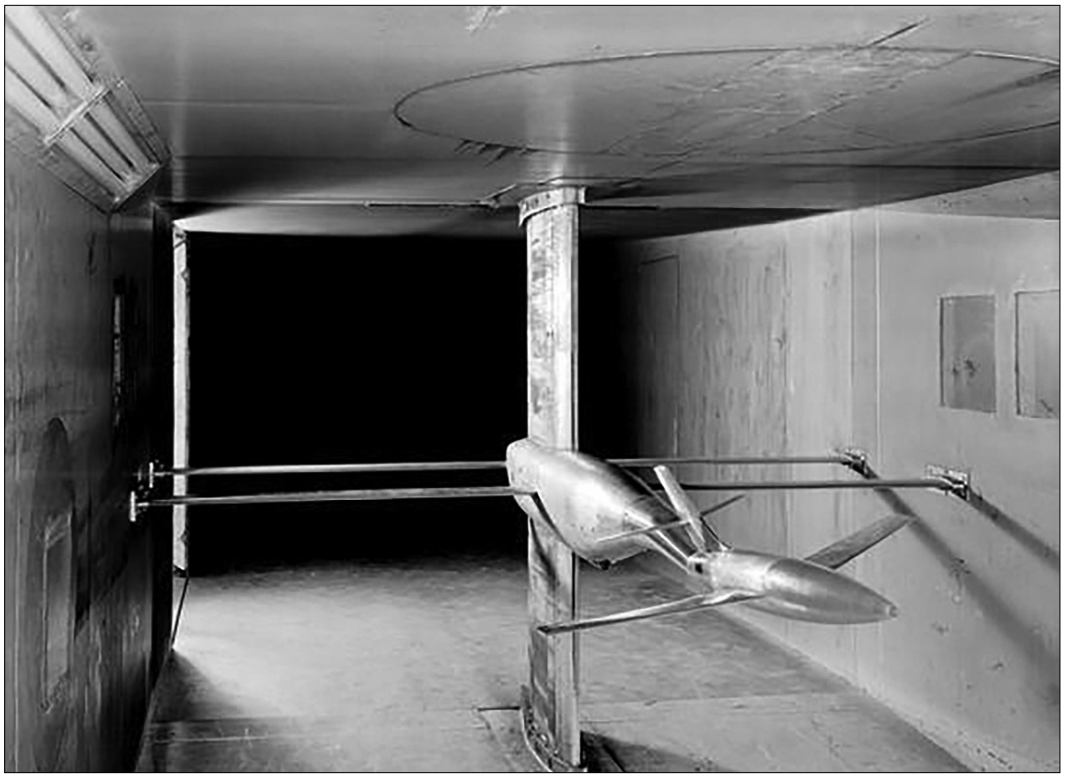


This view from the shop area into the test section in 1947 shows the level floor that facilitated the movement of models between the two areas. (Photo credit: NASA LRC-1947-B701_P-54318)



This plan drawing depicts the 7- by 10-Foot High-Speed Wind Tunnel as it entered service in 1945. Note the test section, fan, and dual towers for air exchange. (Image credit: NASA)

The transonic bump in the 7- by 10-Foot High-Speed Wind Tunnel in 1947 (left) and a half model installed on the bump in 1949 (right). While both half models and sting-mounted full models were used, half models were more common. The models were small to make sure that they were completely within the area of stable transonic flow over the bump and that they did not choke the tunnel at a subsonic speed. (Photo credits: NASA LRC-1947-B701_P_F001-52348 and NASA LRC-1949-B701_P-60740)



This apparatus, seen here in 1951, forced the model, an early X-2 concept, to roll in the airstream. (Photo credit: NASA LRC-1951-B701_P-70082)

GUST TUNNEL

Exterior view of the Gust Tunnel in 1947. (Photo credit: NASA LRC-1947-B701_P-53693)

SIGNIFICANCE

The Gust Tunnel was one of several facilities built at Langley to investigate airplane handling and behavior characteristics, particularly during conditions involving unsteady flow. Like the spin and free-flight tunnels, the Gust Tunnel used dynamically scaled models in free flight and recorded their motions photographically. This tunnel, the first of its kind, provided valuable information that was used to validate early theory regarding flight through unstable air.

DESCRIPTION

The Gust Tunnel, located in Building 1218, was not a true wind tunnel in the conventional sense, but rather a free-flight range where dynamically scaled model airplanes were catapulted into free flight across a test field where vertical jets of air simulated transient air currents and turbulence impinging on the model. The test field measured 14 feet long by 8 feet wide, and it was equipped with a curtain at the end to catch the model. Flat-black panels served to provide a uniform backdrop for photography.[156] The catapult was powered by compressed air, and its launch speed and acceleration rate were adjustable to suit the particular model and test conditions desired. It was able to launch models with wingspans of up to 6 feet at speeds of up to 100 mph. The catapult

launched models along a 5 percent descending grade, although an adjustable carriage determined the model's initial angle of attack upon release. The object was to achieve steady, level flight immediately upon separation, prior to encountering the gust flow.[157]

In essence, the free-flying model flew through the open test section of a vertical wind tunnel, with the upward flow furnishing a sudden "gust" of wind perpendicular to the model's normal flight path. A 75-horsepower variable-speed electric motor turned a blower to generate this air, which was directed to the base of the test field and turned upward. Technicians installed screens at the nozzle opening to shape and direct the gust flow as desired. Above the test field, a flared inlet captured the flow and passed it through a return duct to the blower. Except for the catapult, the entire apparatus was enclosed in a large room so that air outside the test field was calm. A simple control panel controlled the gust flow and model launches.

HISTORY

The Gust Tunnel was one of several Langley responses to address problems associated with how airplanes flew and handled in the dynamic atmosphere of the real world. Stable, uniform flows were needed for many studies involving the basic aeronautical design of aircraft. These studies could be repeated as needed in most wind tunnels to allow engineers to accurately evaluate changes in their designs. These studies greatly helped designers develop practical, efficient airplanes, but they were of virtually no use for studies of how those same airplanes behaved in turbulent air or other adverse conditions.

Gusts, winds blowing transversely to the direction of flight, were one such problem. A gust could, and frequently did, knock a plane off course and into a different attitude, something that could be very serious at low speeds near the ground, as the pilot might not have room to recover from a serious disturbance. The problem was not new. In fact, Jerome C. Hunsaker, later chairman of the NACA Main Committee, had performed some tests involving gusts in the Massachusetts Institute of Technology's 4-Foot Tunnel as early as 1915, and researchers were trying to develop a useful theory that would predict an airplane's response to such non-steady-state events.[158]

In 1937, Langley engineer Philip Donely assembled a simple apparatus on the first floor of the Full-Scale Tunnel Building (Building 643) that he hoped would support useful experimentation in gust conditions. What he termed a "gust tunnel" was a squirrel-cage blower connected to a rectangular duct with a 90-degree turn to blow air upward out of an opening 6 feet wide by 8 feet long. Donely manually fitted screens of different meshes to direct and characterize the flow. He then rigged up a catapult to launch models into free flight above the tunnel's outlet. Its track consisted of two taut aircraft cables, and the carriage riding on them was pulled by a falling weight. He could adjust the upper end of the track to change the catapult's angle of descent, and the carriage had an adjustment to set the model's angle of attack. The catapult could launch models with wingspans of up to 3 feet at speeds of up to about 60 mph. After traversing the gust field, the model

struck a screen of vertical rubber bands that slowed it. Just beyond the screen was a panel of burlap fabric, which snagged a barbed hook on the model's nose to capture it.[159]

Test flights were recorded in two ways. Each model carried a photographically recording accelerometer that measured the vertical accelerations as light traces on moving film. Two stationary cameras captured the path traveled. A flat-black backdrop furnished a uniform background. The model had small lamps in its nose and tail, so with the room darkened, the open camera shutters would record their traces on film. One of the two cameras had a rotating shutter disk in front of the lens so that its trace consisted of dashed lines, from which the model's speed could be determined. Spotlights with slits were also available to project reference lines onto the background as desired.[160]

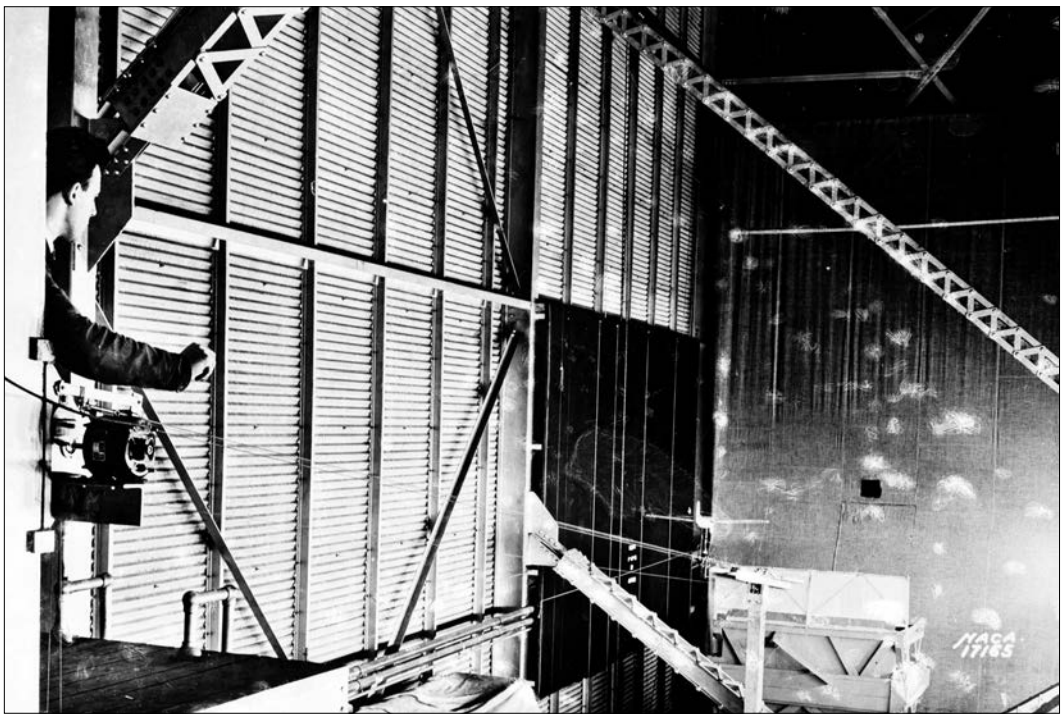
Rudimentary as this apparatus was, Donely and his associates were able to perform significant work with it to describe how airplanes behaved in vertical gusts and how different aspects of wing and tail design affected that performance. The accelerometer records also indicated that gusts could impose loads on an airplane's structure as high as five times those experienced in level flight.[161]

Their work continued through World War II, and the results finally justified the construction of a permanent facility in 1943. Built in Building 1218 in the West Area and opened in 1945, the new Gust Tunnel incorporated the concept and methodology Donely had pioneered in the first apparatus, adding numerous refinements and the ability to handle models twice the size. Instead of a duct blowing into the room, this gust tunnel was a closed-circuit tunnel with an open, vertical test section 8 feet wide by 14 feet long. A variable-speed fan, driven by a 75-horsepower electric motor, allowed technicians to set the gust speed needed, typically in the range of 4–40 feet per second. As before, screens were used to tailor the gust's direction and profile. The cable-track, weight-driven catapult was replaced by a steel-frame, air-driven one similar to those used aboard naval vessels. This offered improved control and enough power to launch models with 6-foot wingspans at 100 mph. With launch speed settable by controlling the air pressure, the catapult was mounted at a fixed 5-degree angle.[162]

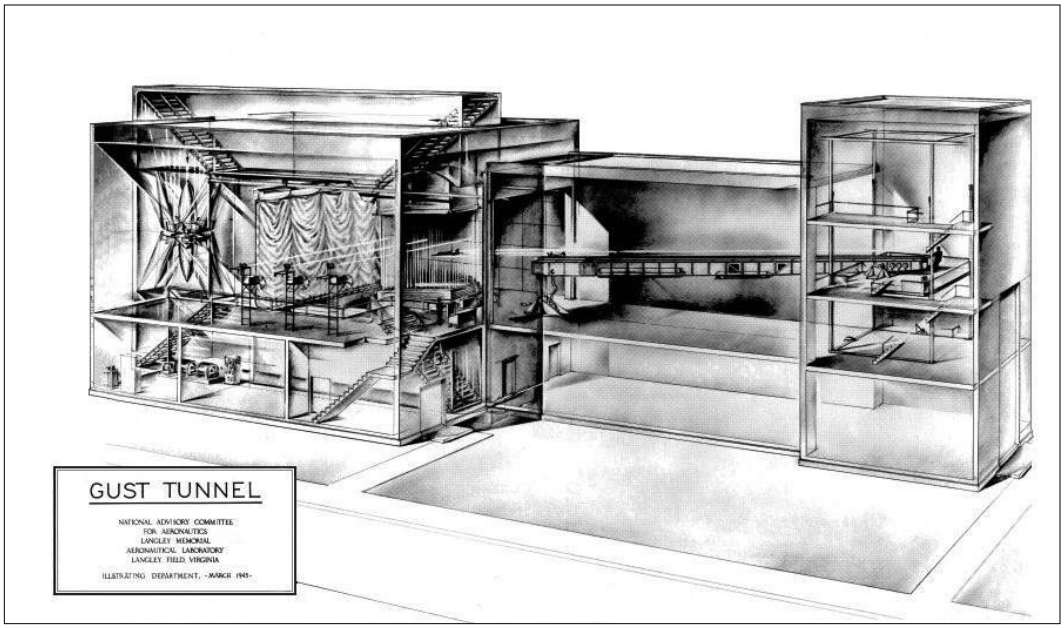
The initial test techniques employed in the new facility resembled those already proven, but the capabilities of the new facility allowed additional methods to be developed. Improvements in photographic techniques and in on-board instrumentation increased accuracy and provided better recording of test flights. Since the models were dynamically scaled, it was possible to begin to experiment with models that were elastically scaled as well. This permitted tests to see the effects of wing deflection in an unsteady airstream. Early models used an arrangement with the two halves of a high wing meeting at a knife edge above the fuselage and struts attached to springs inside the fuselage. While primitive, these were the forerunners of the highly sophisticated models now used in aeroelasticity studies. By the mid-1940s, theorists at Langley and elsewhere had begun to produce mathematical functions to describe and predict flight in unsteady conditions, and the Gust Tunnel was the best place to validate those formulas.

Accordingly, an increasing number of NACA reports reflected efforts to make theory and empirical results agree. The ultimate result was information that aircraft designers could use to refine designs with greater confidence.[163]

The Gust Tunnel continued in service for two decades, but it could not produce the higher speeds and Reynolds numbers increasingly needed during the jet age. Improved theory and the adaptation of some of the Gust Tunnel's techniques to other wind tunnels rendered it obsolete. After limited use in low-speed instrument testing and acoustic research, the Gust Tunnel was dismantled in 1965, and Building 1218 was modified for other uses.[164]



A researcher operates a small model in the Gust Tunnel in 1939. (Photo credit: NASA LRC-1939-B701_P-17165)



This phantom drawing shows the general arrangement of the Gust Tunnel opened in 1945. The tunnel that generated the vertical airflow is in the left building. Note the inclined catapult that launched the model planes into free flight through the vertical current of air. (Image credit: NASA L-43086)

A view of the Gust Tunnel in 1945. The end of the catapult is visible at the center, and the catch screen is on the left. (Photo credit: NASA LRC-1945-B701_P-44363)

4.5-FOOT FLUTTER TUNNEL

Exterior view of the 4.5-Foot Flutter Tunnel and Building 1229A. (Photo credit: NASA LRC-B701-45826)

SIGNIFICANCE

The 4.5-Foot Flutter Tunnel (FT) was Langley's first wind tunnel designed and built specifically to investigate aircraft flutter. It was one of the early tunnels to employ interchangeable test sections, and the first tunnel at Langley to use both air and a heavy gas, dichlorodifluoromethane (R-12), as test media.

DESCRIPTION

The FT, located just west of Building 1229 in Langley's West Area, was a closed-circuit, variable-pressure, steel-shell wind tunnel. It had a circular cross section throughout and featured mitered corners with turning vanes and two interchangeable test sections 4.5 feet in diameter. A brick building (1229-A) enclosed the test section and controls for the FT. Internal heat generated by the drive and solar heat loads were removed by water circulating through cooling coils and a cooling tower located at the southwest corner of the building.[165]

The two interchangeable test sections were fitted with removable castors so they could be rolled into a nearby model shop for model installation, and lugs for lifting by an overhead hoist in the test chamber building. Clamps allowed easy connection to the fixed portion of the tunnel. Each test section was fitted with 17 ports for observation and photography in addition to hardware for mounting models.

A 1,000-horsepower, variable-speed electric motor turned a fan to produce the airflow. This arrangement could generate speeds from 0 to about Mach 1, though this was reduced with a model installed, since the FT was built before test section slots were discovered. The most reliable data were obtained below about Mach 0.8.[166]

The FT was equipped to mix air and R-12 in varying proportions and pressures. Early references give the tunnel's pressure range as 4.3–30 inches of mercury (approximately

2–14.7 psia, or 0.14–1.0 atmosphere), but later surveys indicate an upper pressure of 1.8 atmospheres (26.5 psia).[167]

HISTORY

The significant increase in aircraft speeds during World War II presented some new challenges to aircraft designers. As speeds approached Mach 1, problems in areas like compressibility and vibration loomed increasingly large. Both had been known for some time, but they became major design considerations as airplanes started to enter the transonic (above about Mach 0.7) regime. Compressibility, though complicated, was strictly an aerodynamic phenomenon, but flutter involved a complex and poorly understood interaction between aerodynamic forces (fluid mechanics) and the structural dynamics of airframes (solid mechanics). The field is known as aeroelasticity, and flutter is the unpleasant result when aerodynamic forces generate unstable, often destructive, vibrations in an airframe.[168]

Aircraft structures must be strong, but light as well, and this means they will be relatively flexible. All materials possess a mass characteristic called inertia, and all are elastic to some degree. To complicate matters, the stiffness of a part or assembly is strongly affected by its shape, too. Every part or assembly will have certain resonant frequencies, and an excitation force at that frequency will cause a sympathetic vibration that can increase in magnitude and get out of control. Long, thin items such as wings will flex both in bending and in torsion, and if both modes are resonant at similar frequencies, they can reinforce each other and cause catastrophic failures, sometimes within seconds. This is but one example of the myriad ways that flutter can occur. Aeroelasticity testing identifies design and operating conditions that can cause damaging flutter to occur.

Langley engineers built the FT in 1945 specifically to perform aeroelasticity testing to answer "the detailed questions of what kind of stiffness, how much stiffness, how to attain it; how much mass balance, where to put it, what modes to balance against; how much damping is needed, how reliable is the damping available, [and] how 'irreversible' is irreversible when applied to control surfaces such as tabs."[169] Answering questions like these required the tunnel and the models tested in it to possess some unique features.

No record of the design process is known to exist, but something of the designers' understanding of the problem and their thought processes can be gleaned from brief descriptions of the apparatus found in two NACA technical notes. They were aware from both experience and theoretical predictions that the highest aerodynamic forces occurred at the maximum dynamic pressure, now termed "Max Q," which was at Mach 1, and they specified a tunnel that would come as close to this speed as practical at the time. More importantly, they realized that the density and speed of sound varied in different gasses. In particular, Mach 1 for one refrigerant, dichlorodifluoromethane, better known by its duPont trade name Freon-12 or R-12, was at about half the absolute speed of Mach 1 in air. A steam ejector would easily reduce the pressure down to 2 psia. By using R-12, air, or a mixture of the two, and varying the pressure, hence density,

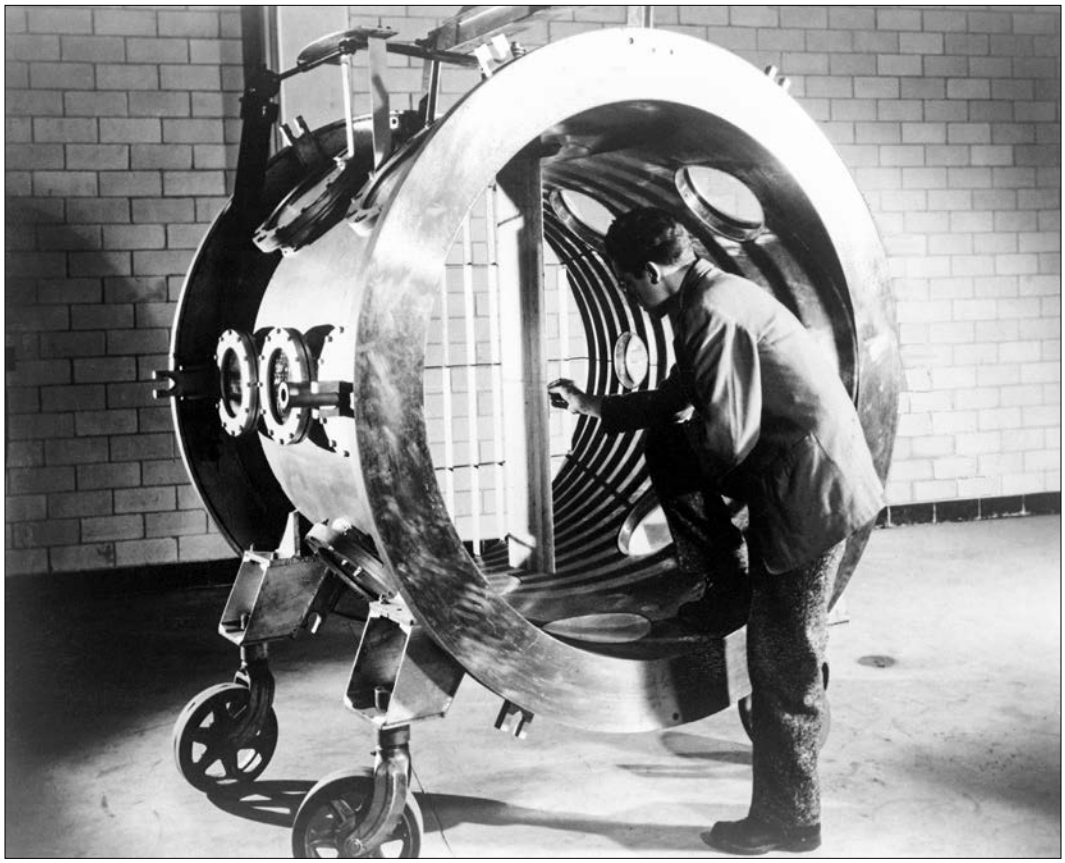
in the tunnel, researchers could vary the mass ratio, Mach number, and Reynolds number independently for any given model. For a reasonably large, 4.5-foot-diameter test section, the use of R-12 allowed speeds of up to Mach 0.9 with a drive motor of only 1,000 horsepower.[170]

The FT entered service in September 1945, just in time to explore the demanding new conditions of transonic flight. New jet planes under development, such as the F-86 and B-47, featured thin, swept-back wings and tail surfaces. Their wings in particular would be subjected to high aerodynamic forces, and their thinness put decided limits on their stiffness. Both manufacturers and the NACA looked for practical design solutions that could be quickly implemented, such as weights to alter the mass and inertia of control surfaces, but also for a thorough understanding of the various aeroelasticity phenomena to better predict and avoid problems.

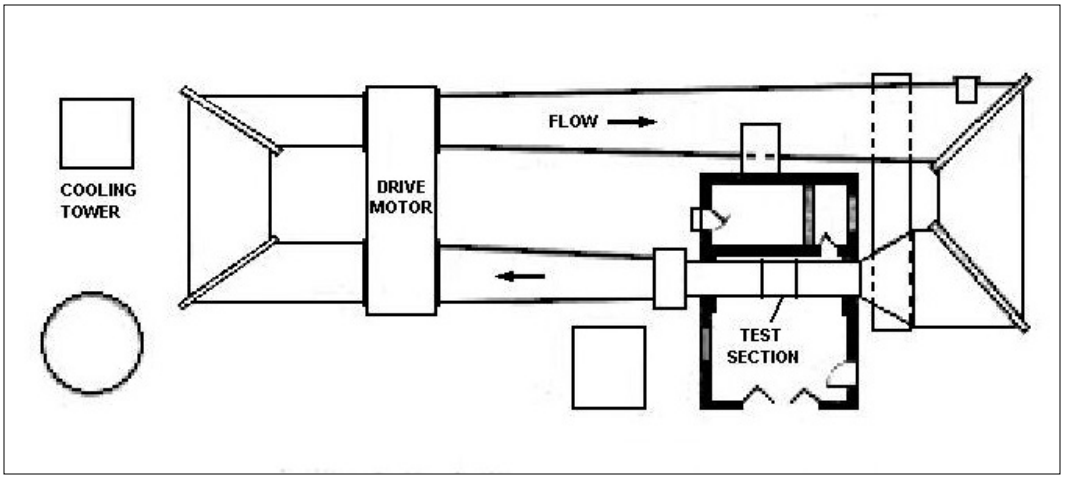
Researchers at Langley's FT realized that all parts of an airplane flexed and interacted dynamically, but they also understood the difficulty of building a dynamically scaled model of a complete airplane that was uniformly accurate, a problem that increased with smaller models. Consequently, they decided to concentrate initially on wings. These models were generally mounted vertically in the tunnel, either on upper and lower bearings or cantilevered from a rigid upper mount. The model wings were typically fabricated of balsa wood with an aluminum insert machined to provide the desired degree of stiffness. Bending and torsional stiffness were determined experimentally with static loadings. Strain gages mounted on the wing yielded oscillograph traces that indicated the frequency and amplitude of any flutter.[171]

The FT quickly proved to be a useful tool for investigating a variety of parameters that affect flutter, and the NACA published numerous reports describing tests done there during the 1950s. Some of these involved novel design concepts, while others explored more mundane, but nevertheless vital, topics. The success of this work and the corresponding increase in the sophistication of flutter models did much to justify the NACA's decision to convert Langley's 19-Foot Pressure Tunnel into a larger aeroelasticity tunnel, the 16-Foot Transonic Dynamics Tunnel (TDT), in 1954. While the focus of aeroelasticity work at Langley shifted to the TDT after its 1959 opening, particularly for semi-span and complete aircraft, the FT continued to be quite useful for inexpensive component testing and research well into the 1980s.[172]

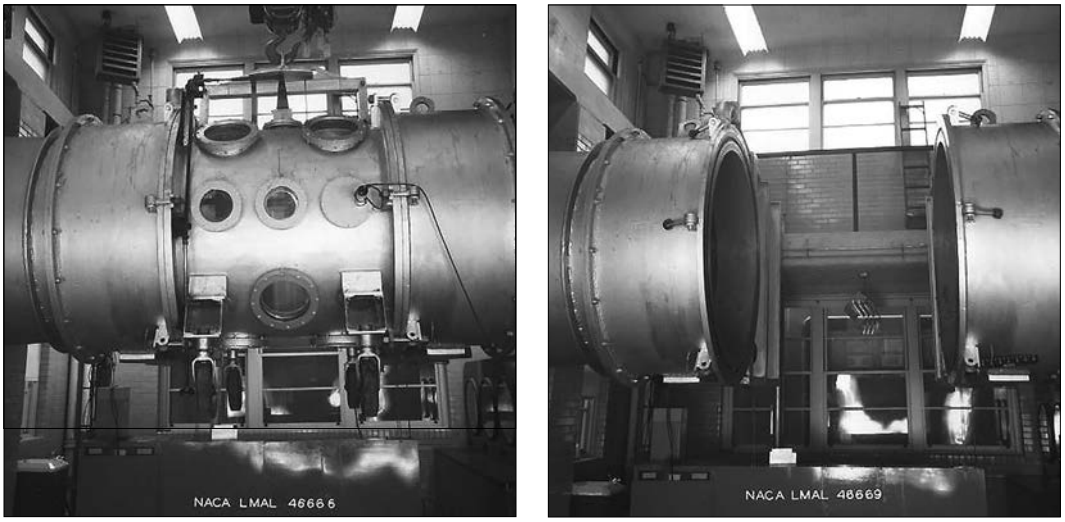
Budgetary pressures on NASA during and after the late 1980s caused the agency to reevaluate its facilities against the changing research needs of the aerospace industry. The FT was one of a number of wind tunnels at Langley considered to be redundant and/or obsolete. Accordingly, it was closed and demolished shortly thereafter. The brick building that had served as its test chamber had its tunnel penetrations bricked in, and it served as a storage facility for several years until it, too, was razed in 2008. Thus, nothing of the 4.5-Foot Flutter Tunnel remains.



A researcher in 1946 inspects a model wing mounted vertically in one of the 4.5-Foot Flutter Tunnel's test sections. What appear to be ribs inside the test section are actually shadows cast by the flow straightener at the far end. (Photo credit: NASA LRC-1946-B701_P-46834)



This plan drawing of the 4.5-Foot Flutter Tunnel shows the location of its removable test section within the test chamber building. (Image credit: NASA)



These two photos from 1946 show the 4.5-Foot Flutter Tunnel's test section attached to an overhead hoist for removal (left) and the tunnel after its removal (right). Two interchangeable test sections were available, allowing tests to be run in one while a different model was being installed in the other. Note the multiple observation ports and clamps to ease removal and installation. (Photo credits: NASA LRC-1946-B701_P-46666 and NASA LRC-1946-B701_P-46669)

11-INCH HYPERSONIC TUNNEL

The 11-Inch Hypersonic Tunnel is seen here in 1950 with two key people who championed its design and construction, John V. Becker (left) and Charles H. McLellan. They led some of America's most important early research into ultra-high-speed flight. (Photo credit: NASA LRC-1950-B701_P-63887)

SIGNIFICANCE

The 11-Inch Hypersonic Tunnel (11-Inch HYST), originally named the 11-Inch Pilot Hypersonic Tunnel, was Langley's first wind tunnel designed to exceed Mach 5. Intended to be a developmental tool for establishing the design criteria and specifications for a larger hypersonic tunnel, the 11-inch tunnel not only fulfilled that role, but it proved to be a valuable research tool in its own right, so much so that "Pilot" was dropped from its name, and it was relocated from the East Area to a newer building in Langley's West Area. Some of the NACA's most renowned hypersonic researchers began their investigations in this facility, and solutions for many of the problems inherent to all hypersonic tunnels were first tested here. With over 230 technical reports based on work done in it, the facility was one of the NACA and NASA's most productive facilities.

DESCRIPTION

The 11-Inch HYST was an amalgam of a blow-down tunnel and a closed system. Externally, the tunnel itself appeared as a pair of elongated steel boxes with square cross sections. The smaller of the two contained the nozzle and test section, which was equipped with two circular windows ground optically flat for schlieren photography. Connected to it was a larger section that contained the second minimum diffuser. A 2.5-inch supply pipe

from a 400-cubic-foot high-pressure reservoir conveyed test air through a pressure regulator and into an electric heat exchanger. From there, a 4-inch pipe passed the heated air through a quick-acting valve immediately upstream of the nozzle, which expanded into the test section. From the diffuser's exit, a 24-inch pipe passed the air through another valve and into a 12,000-cubic-foot vacuum tank. Prior to a test run, a vacuum pump pulled most of the air in that tank and discharged it to a compressor. The three-stage compressor compressed the air to 735 psi and pumped it through an oil filter and desiccant dryer to the high-pressure reservoir. In operation, the tunnel functioned as a blow-down tunnel driven by the differential pressure between the reservoir and vacuum tank, but the closed vacuum pump-compressor circuit allowed the system to retain and reuse its air. This was crucial to maintaining the very dry air needed for successful hypersonic operation. When needed, a second vacuum pump reduced the vacuum tank's absolute pressure further.[173]

When the tunnel was moved to Building 1229 in the West Area from the Propeller Research Tunnel in the East Area, the physical arrangement of the air-supply components changed somewhat to suit the new site, but the functional arrangement and tunnel operation remained the same.

HISTORY

The hypersonic flight regime is generally defined as being above Mach 5, though that definition is imprecise. It begins at the speed where aerothermal effects, or aerodynamic heating, become significant. Vehicles flying at hypersonic speeds must endure high temperatures as well as aerodynamic forces, and the high temperatures mean that the chemistry of the air becomes increasingly important, since the various gasses that make up the atmosphere have different thermodynamic properties. With more parameters to consider, the hypersonic regime is considerably more complex than the slower speed ranges, both theoretically and empirically.[174]

German engineers at Peenemünde built the first blow-down tunnel that could achieve near-hypersonic (Mach 4.4) speed in 1943, and they were building one intended to reach Mach 10 when World War II ended.[175] Much of the German literature on supersonic and hypersonic research ended up in the United States, where John V. Becker, assistant chief of John Stack's Compressibility Research Division at Langley, took a particular interest in the subject. Soon after gaining knowledge of the German work in mid-1945, Becker proposed the construction of a small pilot tunnel to investigate and solve the formidable problems before attempting to build a larger, permanent hypersonic tunnel. Despite some opposition, the proposed pilot tunnel was cheap, and the NACA's Main Committee authorized $39,500 for it. Becker assigned Charles H. McLellan, another engineer in the division, to lead the design team.[176]

Space was available in the old Propeller Research Tunnel Building (originally Building 103, the current location of Building 640), and Langley machinists fabricated most of the components. While McLellan used the best knowledge of the day in the

design, the design process revealed that much remained to be learned, and considerable debugging was needed to make the tunnel function well. Operational status was finally reached in November 1947.[177]

Two problems were particularly vexing: nozzle design and liquefaction. Hypersonic tunnels utilize the same type of converging-diverging nozzle as supersonic tunnels, but the expansion ratio is 5 to as much as 100 times greater, depending on the desired speed. The contour of the nozzle expansion is critical to managing the shock waves that will develop. Hypersonic speeds also necessitated much higher input pressures to the nozzle, requiring huge compressors for continuous-flow operation. Consequently, most hypersonic tunnels, including the 11-Inch HYST, were blow-down tunnels, where more-practical compressors could pressurize a supply reservoir and/or evacuate a receiving tank before a test run. Fortunately, quick-responding instrumentation made short runs viable. Early nozzles, even when successful in achieving speed goals, were very inefficient, and the team devoted considerable energy into improving them. Nozzles evolved from three-dimensional ones with both horizontal and vertical expansions to two-dimensional nozzles that utilized a narrow slit at the throat and expanded in only the vertical direction. As intended, the tunnel's design facilitated easy nozzle changes. Both single- and two-stage nozzles were tested. A two-stage design reached Mach 6.5, but rotational flows made the useful test area too small. Ultimately, a two-dimensional, single-stage Mach 6.9 nozzle proved to be the most satisfactory. Closely related to nozzle design was the configuration of the diffuser, which in hypersonic tunnels usually includes a second minimum (i.e., a second contraction, followed by an expanding diffuser) to reduce the air velocity in a manner that minimizes expansion shock formation. Like the nozzle-test section, the diffuser was designed as a bolt-in section that could be reconfigured to obtain the best performance.[178]

The second hurdle was air liquefaction, not condensation of water vapor in the air (which could be managed with the closed system and desiccant dryer), but the air itself changing to its liquid phase as it left the nozzle throat. In a converging-diverging nozzle for supersonic speeds, energy is converted, essentially adiabatically, from pressure into velocity. The air cools somewhat, but the effects are generally negligible. That is not the case in hypersonic nozzles, which have much larger expansion ratios. For the air to accelerate to Mach 5 and above, it must convert into motion not only pressure, but also its own latent heat, thereby lowering its temperature. As the rate and amount of this conversion increase, the temperature drops to the point where the combination of low temperature and pressure push at least some of the gasses that make up air into their liquid state. At Mach 5, for instance, even 200°F inlet air will drop to –350°F in the test section—below the condensation points of oxygen (–297°F) and nitrogen (–320°F). Liquid droplets of any supercooled gas will typically start to form around minute particles in the air, and they are extremely detrimental to aerothermodynamic research, with liquefaction of the test medium itself especially onerous. The solution involved heating the nozzle inlet air to several hundred degrees. For this, McLellan's team included an

electric heater to heat incoming air. (This worked reasonably well for a small tunnel, but later tunnels would need more exotic heaters to accomplish the task.)[179]

Charles McLellan seems to have directed most of this development work, leading extensive studies of both dual- and then single-stage nozzles. He elected to develop a nozzle for a speed of about Mach 7. Such a nozzle would need an expansion ratio greater than 100:1, so he first sought to do that in two stages. The first stage expanded horizontally, while the second stage expanded vertically. The combination worked, but it induced some rotational motion that made the usable area for a model small and somewhat unpredictable. A single-stage nozzle solved the rotational-flow problem and achieved the same speed. It was, however, very difficult to machine and maintain. Machining tolerances of ±0.001 inch were required, but warpage of up to 5 times that was sometimes experienced during tests, due to temperature changes and support flexibility. These had the effect of lowering the speed a little and shortening run times by requiring greater energy, demonstrating the extreme sensitivity of hypersonic tunnels.[180]

Another problem involved the heat exchanger, which initially was a bundle of copper tubes surrounded by electric heating coils inside a well-insulated case. The heating coils preheated the tubes, which then heated air flowing through them during a test. The problem was copper oxidation at high temperature, which formed an oxide scale that flaked off during tests. Limiting the temperature to around 850°F helped, but changing the tubes to steel finally solved the problem and allowed temperatures to more than double.[181]

Becker and McLellan originally equipped the tunnel with a fixed diffuser. As with the heater, it worked, but at a high pressure differential. Replacing this with a diffuser incorporating an adjustable, second minimum reduced the required pressure differential dramatically and increased the typical run from 30 to 90 seconds. Installation of a pressure regulator ahead of the heater also improved settling-chamber pressure control and, thus, test-condition control, which further enhanced usable run time.[182]

Once in service, the 11-Inch HYST proved to be a very productive facility. During its 25-year life at Langley, researchers at the tunnel produced technical papers at an average rate of almost one per month, an astounding amount for any research facility. Some of the test programs looked at specific aircraft and missile designs, both conceptual and actual, while others were closer to pure research programs to investigate the basic nature of hypersonic flow and validate theoretical work. As originally intended, the little tunnel also provided a wealth of information and operational experience that was directly applicable to the larger, permanent facility Becker envisioned, but the usefulness of this tunnel delayed construction of what became the 31-Inch Continuous-Flow Hypersonic Tunnel for several years.

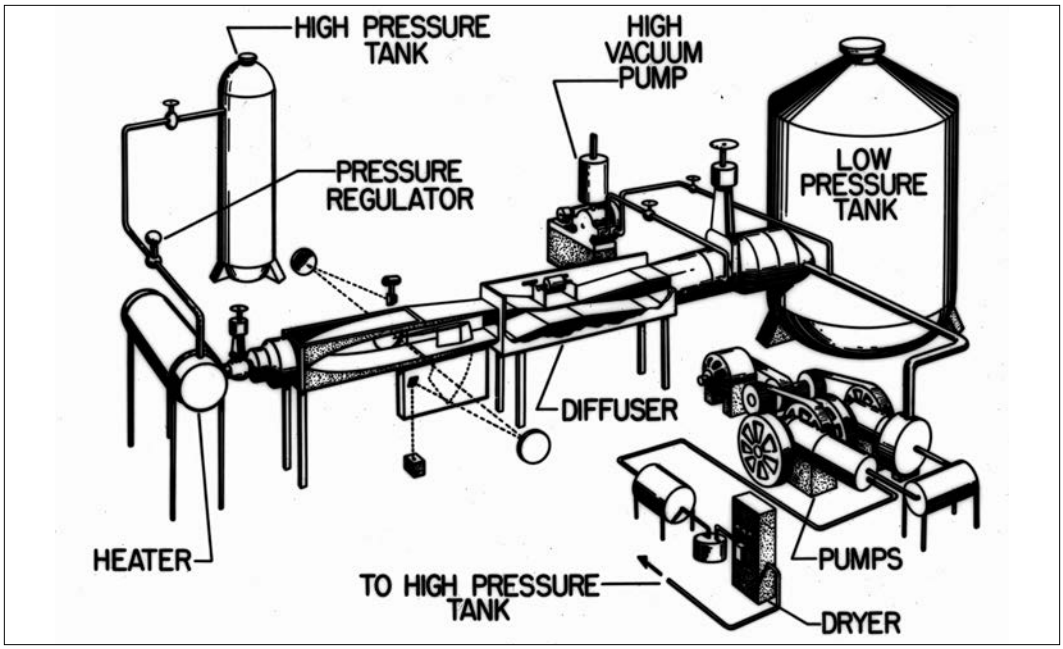
Within a year of its opening, Division Chief Stack decided to remove the "pilot" designation and move the tunnel into newer Building 1229 in the West Area, where any new hypersonic facilities would be built. A free-flight tunnel was almost complete, with part of it located in one end of the building, but the value of the hypersonic tunnel and

associated research was such that the free-flight tunnel was abandoned and its inside space given to the 11-Inch HYST. The move occupied much of 1948. All of the tunnel's hardware, including the complete air system, was reinstalled in and beside Building 1229. Some slight adjustments in physical arrangement and piping were needed to fit the new location, but the tunnel was functionally unchanged. One such adjustment raised the tunnel's centerline to approximately 8 feet above the floor to improve access and reduce the number of pipe bends.

Ultimately, the 31-Inch Continuous-Flow Hypersonic Tunnel was approved and built in Langley's West Area, along with several other hypersonic tunnels designed to explore specific aspects of the flight regime, and the 11-Inch HYST became somewhat dated and redundant. In 1973, negotiations with Virginia Tech in Blacksburg, Virginia, led to NASA donating the tunnel to the school, even appropriating almost $300,000 to help fund the move. It was the third retired Langley wind tunnel given to the school.[183]

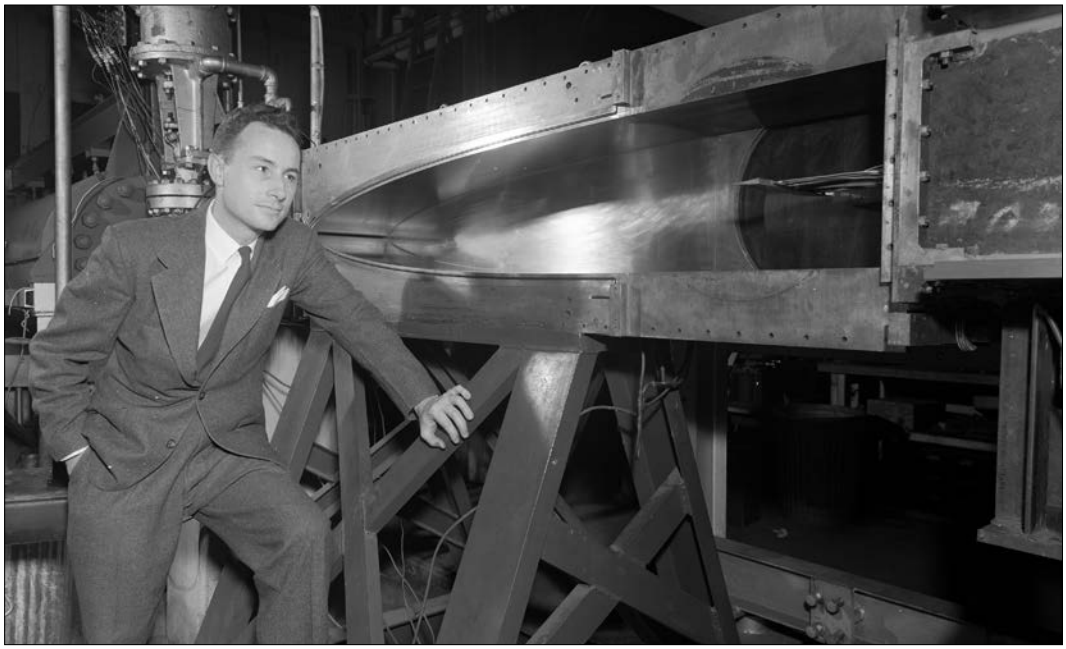
By the time the 11-Inch HYST arrived in Blacksburg, Virginia Tech's administration was having second thoughts about the value of the tunnel. Though the Department of Aerospace and Ocean Engineering pleaded for its installation, it was of no use. The school canceled its authorization to build the support facility and reerect the tunnel. When the tunnel's components arrived, they went directly into long-term storage. Individuals involved at the time do not know if any of the components still exist or, if so, where they might be. In all likelihood, they were sold for scrap on an unknown date.[184]

A technician inspects a Gemini spacecraft model mounted on a sting in the 11-Inch Hypersonic Tunnel in 1962. The photograph was taken for the Public Affairs Office and was not an actual test. (Photo credit: NASA LRC-1962-B701_P-04893)

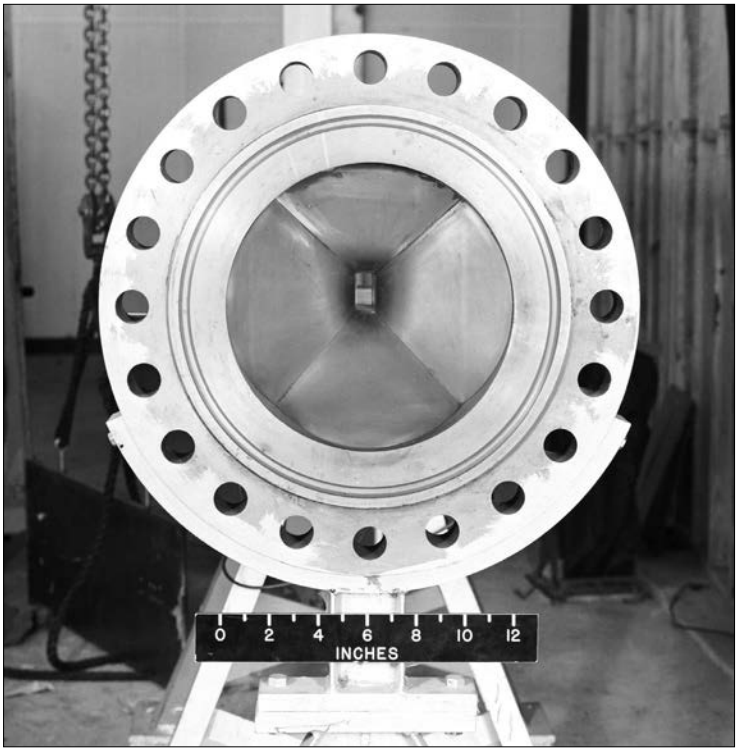


This drawing shows the 11-Inch Hypersonic Tunnel and its air system. The physical arrangement of the tanks and pumps changed slightly when the tunnel was relocated, but their connection sequence remained the same. The drawing is not to scale. (Image credit: NASA LRC-1962-B701_P-01019)

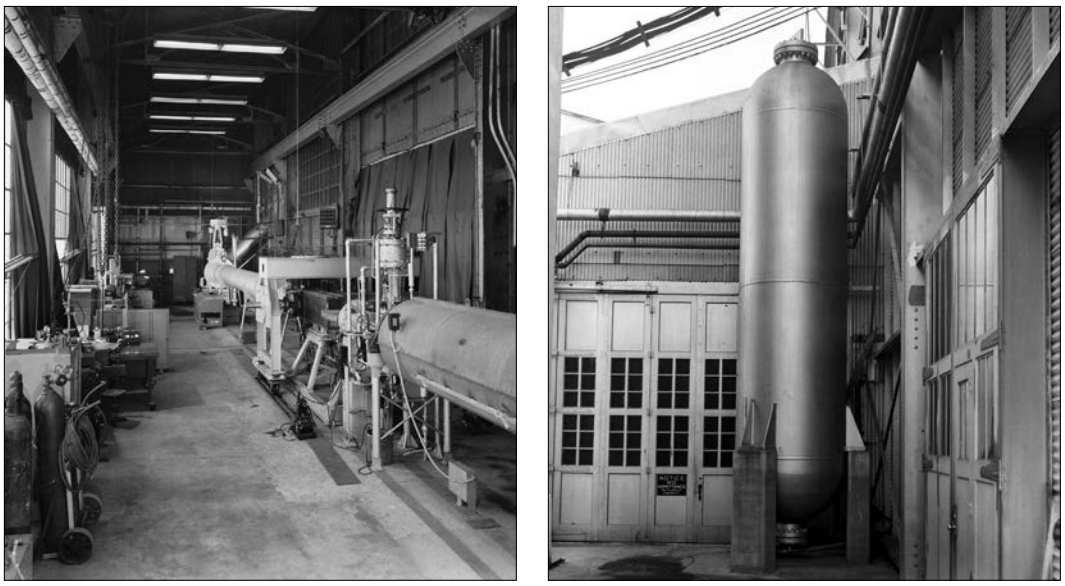
The vacuum (left) and high-pressure (right) tanks for the 11-Inch Hypersonic Tunnel installed at Building 1229. The long duct in the right foreground is a free-flight tunnel that never opened. Its space inside the building was used for the hypersonic tunnel instead. (Photo credit: NASA LRC-1973-B701_P-71336)



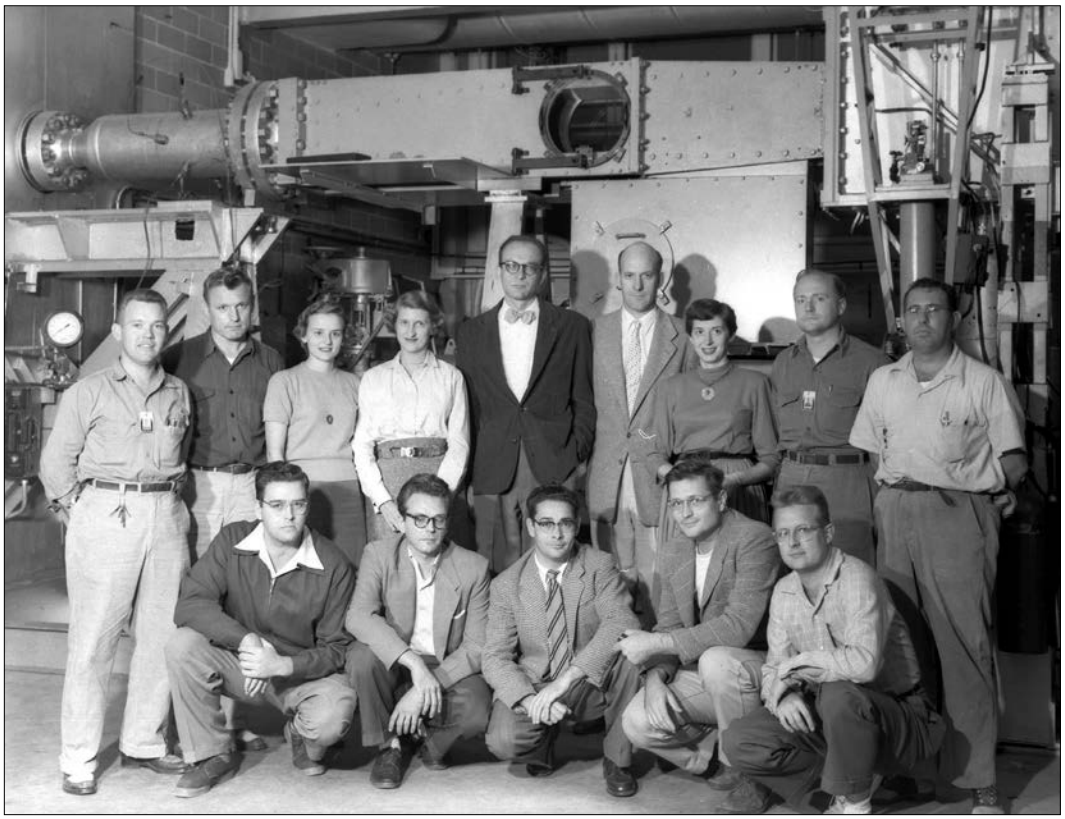
This 1950 photograph shows the 11-Inch Hypersonic Tunnel's large expansion from the nozzle throat—a barely visible slit—to the test section needed to generate hypersonic speeds. The expansion contour had to be precisely machined for the tunnel to function well. (Photo credit: NASA LRC-1950-B701_P-63886)



An end view of one of the early nozzles tried in the hypersonic tunnel in 1949. Nozzle development was a difficult but crucial task for the team. (Photo credit: NASA LRC-1949-B701_P-59098)

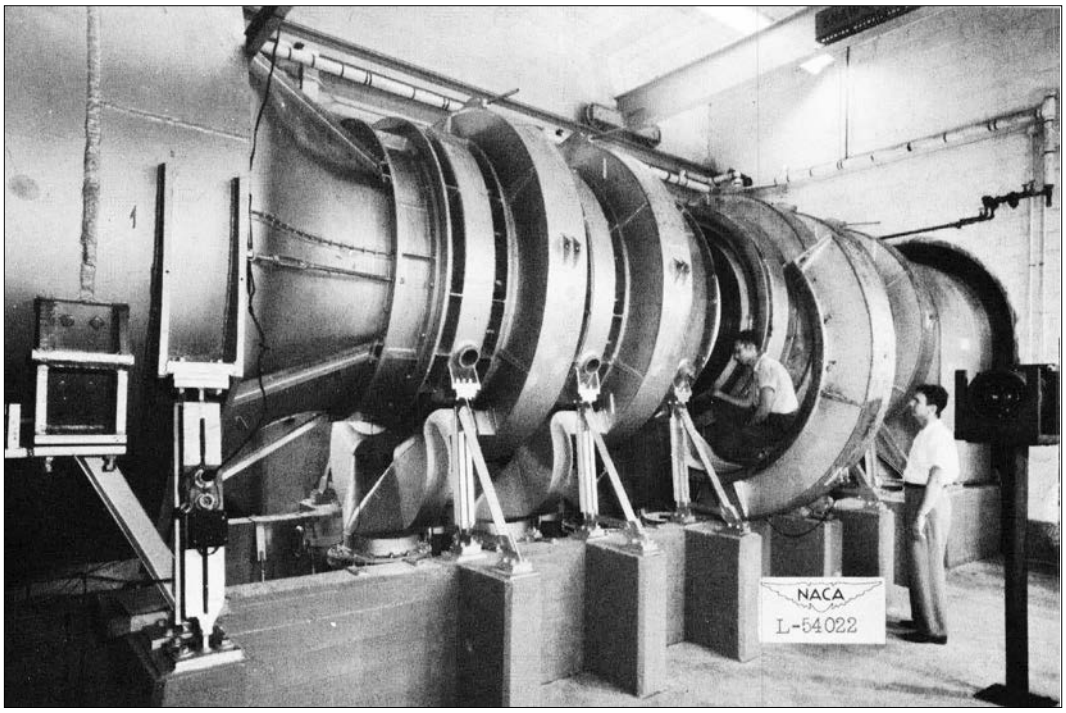


These two views show the 11-Inch Hypersonic Tunnel as it was first installed in the Propeller Research Tunnel Building in the East Area. The test section, seen here in 1948 (left), was under a small gantry that held the schlieren apparatus. Air flow was from front to rear. The vertical, high-pressure tank, here in 1953 (right), was mounted outside the building, as was the vacuum tank. (Photo credits: NASA EL-2000-00265 and NASA LRC-1953-B701-59092)



The 11-Inch Hypersonic Tunnel team poses under the test section of the tunnel shortly after its move to the West Area. Note how the tunnel was elevated when relocated. (Photo credit: NASA LRC-1954-B701_P-86871)

ANNULAR TRANSONIC TUNNEL



A view of the Annular Transonic Tunnel shortly after its completion with the long entrance and three boundary-layer removal duct rings still intact. Louis W. Habel (right) looks on as R. Turner inspects the rotor. (Photo credit: NACA RM-L8A23, Fig. 2)

SIGNIFICANCE

The Annular Transonic Tunnel (ATT) was a novel attempt to find some means of performing transonic research in a laboratory setting before slotted walls made such research practical in a conventional wind tunnel. It was a unique combination of wind-tunnel and whirling-arm technologies to circumvent the choking problem that plagued existing wind tunnels as their speeds approached Mach 1. While limited in size and performance, the ATT did host some post–World War II airfoil research at low transonic speeds.

DESCRIPTION

The ATT was not a wind tunnel in the conventional sense, although its tubular shape did not appear significantly different from other open-circuit tunnels. It was really a whirling arm, a sophisticated version of an 18th-century invention that mounted a model on the end of an arm that was then rotated to move the model through the air.[185] The core of the ATT was a rotating disk, or rotor, 57 inches in diameter, that was driven by dual 200-horsepower DC motors to a maximum speed of about 4,300 revolutions per minute. The disk rotated about a horizontal axis, and its diameter matched that of the inner of two concentric cylinders.[186]

Two concentric cylinders, with a 3-inch annulus between them, formed the tunnel portion of the ATT. Air drawn in through a bell-mouth entrance at one end flowed through the annular passage, induced by an axial-flow fan downstream from the rotor. This fan was driven by a 200-horsepower DC motor, and the combination could produce a maximum axial velocity through the annulus of about 250 feet per second (170 miles per hour). The outer cylinder had a double flare to 108 inches in diameter at the entrance, and it necked down to approximately 36 inches in diameter at the fan. The inner cylinder served to enclose the rotor drive and as a duct for boundary layer removal. One end terminated with an exhaust cone after the fan, and the other emerged from the bell-mouth entrance as a duct to the boundary-layer extraction blower, a centrifugal fan driven by a 300-horsepower motor that exhausted to the atmosphere. Also connected to this duct were three circular plenums that surrounded the outer cylinder ahead of the rotor, though two were removed early in the ATT's life. The arrangement provided for boundary layer extraction from both surfaces of the annulus.

A single airfoil model was attached to the rotor. Access was through a hatch in the outer cylinder. The model's spanwise dimension was always slightly less than 3 inches so that it essentially spanned the annulus without touching the outer surface. The maximum practical chordwise dimension was 4 inches. These airfoils were unique in that they were twisted so that their effective angles of attack remained constant over the full span, even though the rotary motion caused the tangential velocity of a tip to be greater than that of a root. This was possible because the test velocity was the vector sum of the model's rotational velocity and the axial velocity of the annular airstream.[187]

While the model's rotational velocity was far greater than the annular air velocity, the air flow provided three advantages. First, it kept the model from operating in its own wake—a classic problem for all whirling arms. In essence, the model cut a helical path through air it had not yet disturbed. Its second contribution was to allow the angle of attack to be varied by changing the airspeed. Since velocity is a vector quantity, changing the magnitude of one variable causes the resultant angle—the angle of attack—to change as well. The third contribution, and the primary reason the ATT was built, was that the air motion had the same effect as increasing a tunnel's height, thus reducing blockage, in minimizing shock reflection off its walls. The large height-to-model thickness ratio minimized choking effects and made velocities at and slightly above Mach 1 possible. The ATT ran tests in the range of Mach 0.6 to 1.01.

The entire apparatus was supported with its centerline approximately 8 feet above the floor on steel bents resting on a concrete foundation. Its enclosing cinder-block structure stood in the West Area approximately where the Jet Exit Test Facility (Building 1234) now stands.

HISTORY

Between 1943 and 1950, engineers at Langley and elsewhere desperately needed a viable means to investigate the complex aerodynamic regime between about Mach 0.7 and 1.2, now known as the transonic regime. The complex mix of sub- and supersonic flows in this speed range made theoretical analysis very difficult, and shock waves that reflected off tunnel walls prevented empirical testing through most of the regime. With no effective ground-based transonic facility, most available data came from tests of models dropped from airplanes or launched on top of rockets.[188]

Engineers around the world experimented with novel ideas to circumvent the choking problem. Most of these involved removing a portion of the test-section walls—a concept that ultimately worked—but the early experiments left much to be desired. Langley engineer Coleman DuPont Donaldson proposed an entirely different concept in 1944. Donaldson's idea was based on an old device known as a whirling arm. With a whirling arm, a model was mounted on the end of an arm that was then rotated so that the model moved in a circular path. The concept was viable, and with sufficient power Mach 1 could be attained, but after its first revolution the model would be moving through its own wake, not still air, so the actual test conditions could not be known.

Donaldson suggested that the arm be changed to a disk, or rotor, within a controlled airflow. This could be done by creating an annular passage using two concentric cylinders. His rotor would have the same diameter as the inner cylinder, and a model mounted on its rim would extend the width of the annulus, coming as close as possible to the outer cylinder without striking it. With a small tip clearance, the flow would be two-dimensional, simplifying analysis of the data. The rotor would rotate fast enough to produce the desired tangential speed at the model. Moving air axially through the annulus would keep the model in clean air and out of its wake. In fact, changing the air velocity would have the effect of changing the angle of attack, since the model's test velocity would be the vector sum of the model-rotation and axial-airflow velocities.[189]

The practical execution of this idea had problems, but other engineers at Langley had already developed some of the solutions while working on other problems. One such problem involved the varying spanwise velocity of the rotating model, but this was solved by twisting the model spanwise to make the resultant vector (test velocity) the same at all points.

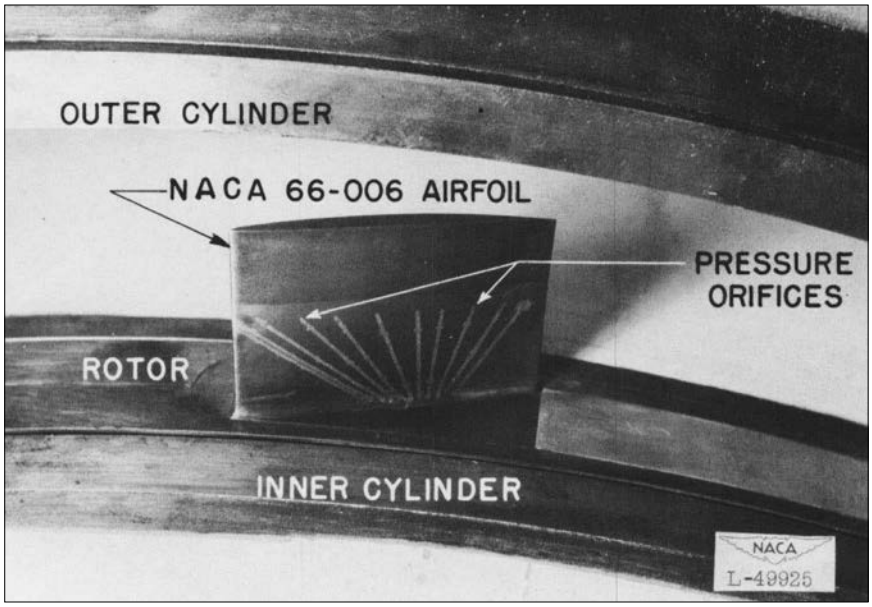
From the outset, Donaldson presumed the primary measurements would be of static pressure distributions read through small holes (ports) across the model's chord at mid-span. While easy to do in conventional tunnels, the most difficult challenge in the ATT project proved to be finding a way to connect static pressure ports on the rapidly spinning model to stationary manometers outside the tunnel. Fortunately, engineer Blake W. Corson, Jr., in the 16-Foot HST, had designed what he called a pressure transfer device for use with studies of axial compressors in that tunnel. It was simple in concept, using mercury that inertia held against the inside of a drum spinning with the rotor to

form a seal between the drum and stationary baffles inside that formed isolated voids, one for each static pressure port. Jack Runckel, Richard Davey, and Mason Miller worked to solve the practical design issues, and the pressure transfer device was adapted to the ATT. It worked, but a later device that replaced the mercury with synthetic rubber seals proved to perform well while being simpler to use.[190]

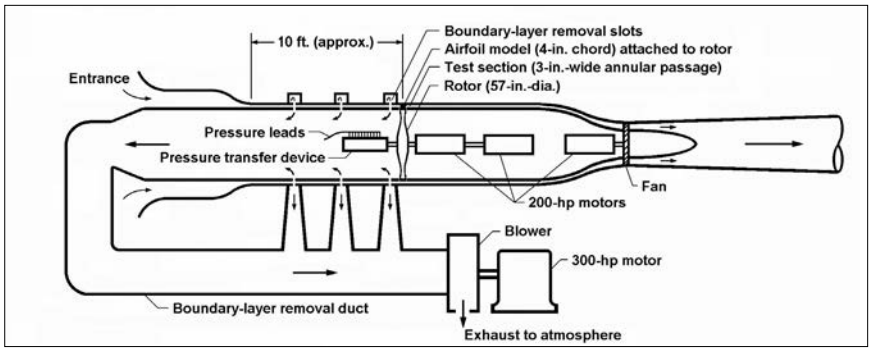
Another significant problem to overcome involved the boundary layers along both annular walls. With only a 3-inch-span model, any boundary layer would have a significant detrimental effect. The team designed the ATT with three sets of circumferential slots in both cylinders, believing that multiple extractions of air next to the walls would deliver almost boundary-free air to the model. The inner cylinder served as the plenum for the inner slots, and three circumferential ducts around the outer cylinder conveyed their extraction air. A duct conveyed all of this air to a 300-horsepower exhaust fan. During start-up testing, the data revealed that this 3-slot system, distributed over a 10-foot-long annulus, had little effect on the boundary layer. The length of the annular path apparently generated greater boundary-layer thickness than the extraction system could remove. To correct the problem, the team decided to remove the first two sets of slots and the long entrance section, leaving only one set of slots and an entrance only 2 feet long. This reduced the boundary layer to almost zero over 70 percent of the span and significantly reduced it at the root and tip.[191]

The ATT opened in 1947, and it functioned more or less as intended after the boundary-layer problem was solved. It could produce stable test conditions from approximately Mach 0.6 to just over Mach 1. While the team initially hoped to achieve Mach 1.1 or 1.2, some structural concerns, apparently stemming from the slightly unbalanced rotor with one model attached, convinced them not to exceed Mach 1. Over the course of five years, the team tested five airfoil models, beginning with the NACA 66-006 design. Data from the ATT generally matched that from other tests, but the pressures measured in the ATT were always slightly higher. The reason for that was never understood.

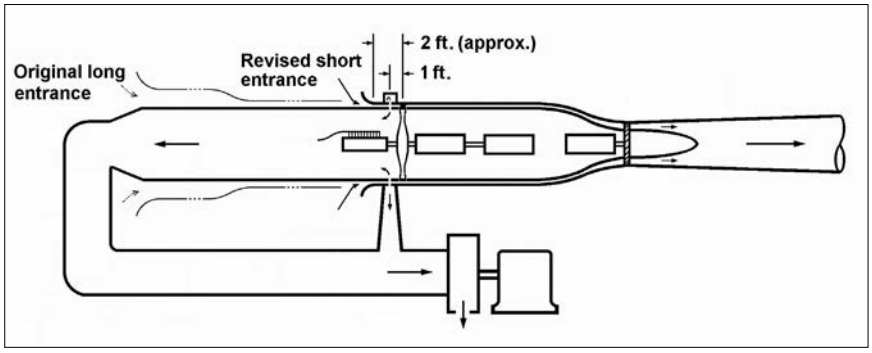
By 1952, Langley's Ray Wright had demonstrated that slotted walls were a very effective way to achieve stable transonic speeds in conventional wind tunnels, and Langley had installed them in its 8-foot and 16-foot high-speed tunnels, with impressive results. With its limitation to small, unique airfoil models and complexity of setup and operation, the ATT was abandoned and decommissioned in 1952 and subsequently demolished. No portion of it survives.[192]



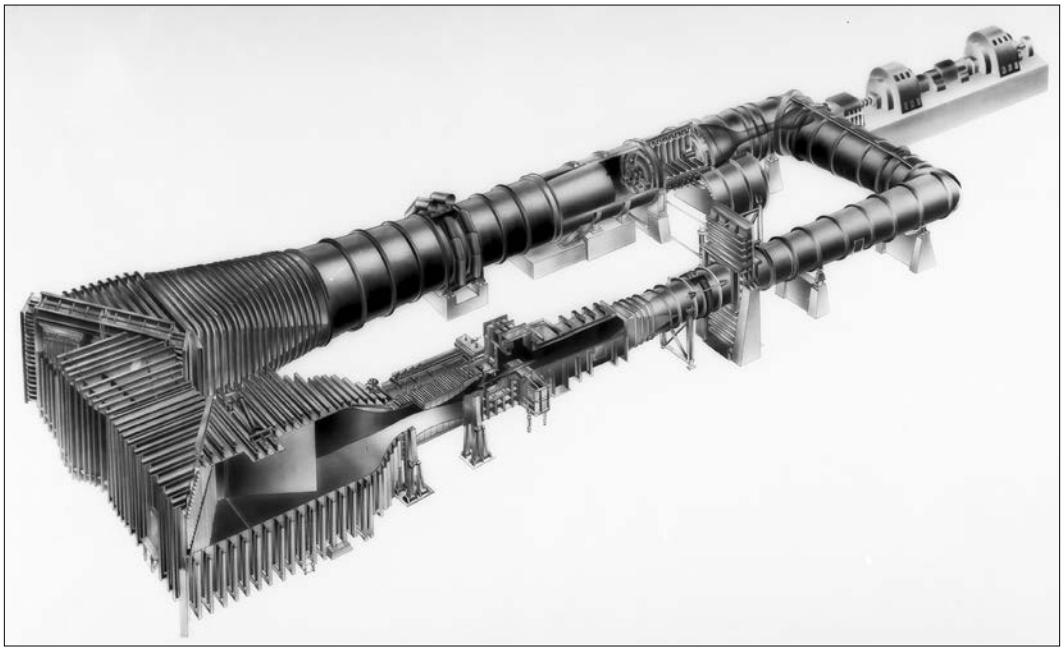
An air foil mounted in the Langley annular transonic tunnel. (Photo credit: NACA RM-L8A23, Fig. 4)



These diagrams show the general arrangement of the Annular Transonic Tunnel as originally built (above) and after its modification to reduce the boundary layer (below). (Image credit: NASA NACA Report 1106, Figures 1 and 4)



4-FOOT SUPERSONIC PRESSURE TUNNEL



This cutaway drawing of the 4-Foot Supersonic Pressure Tunnel shows its heavy steel construction, seven-row compressor, dual motors (after 1950), and flexible-wall nozzle. (Photo credit: NASA LRC-1949-B701_P-60681)

SIGNIFICANCE

The 4-Foot Supersonic Pressure Tunnel (4-Foot SPT) was the NACA's first large supersonic tunnel, and its first wind tunnel featuring a multi-row axial compressor and a variable-contour nozzle for speed adjustment. The tunnel combined these features with pressure control and air-conditioning cooling equipment, making it the first tunnel to incorporate all of the major technologies needed in a modern, continuous-flow supersonic tunnel.

DESCRIPTION

The 4-Foot SPT was a single-return, closed-circuit tunnel erected one block east of the 16-Foot HST in Langley's West Area. Assigned Building Number 1236, the tunnel circuit occupied a space approximately 175 feet by 70 feet, with structures housing the drive motors, model shop, and supporting offices extending beyond that. Like most other tunnels of its era, the 4-Foot SPT was a steel-shell tunnel with external stiffening and support members fabricated out of structural-steel shapes. Designed as a pressure tunnel, although it normally operated at a partial vacuum to simulate altitude, most of the tunnel had a circular cross section. The test section, settling chamber, and return leg between turns 3 and 4 were rectangular, with the test section measuring 4.5 feet wide by 7 feet long. To accommodate the pressure with flat walls and right-angle corners,

these sections required approximately four times the support rib density of the circular portions. The rectangular portions were required to match the necessarily rectangular cross section of the adjustable nozzle. The test section's height varied between 51 and 64 inches, depending on the Mach number set in the nozzle. Each of the side walls was fitted with two 30.5-inch-diameter, optically flat windows to permit schlieren photography. Most models were mounted on a holder called a sting, which was supported on a streamlined horizontal strut stretching between the two side walls. Two lead screws within the strut allowed a ±15-degree adjustment in angle of attack. With this horizontal angle-of-attack adjustment, models were mounted with wings vertical for tests involving variations in pitch. A supplemental rotary sting doubled the range of motion, but this placed the model closer to the walls and, thus, reduced model size for tests up to Mach 1.4 to avoid interference with reflected shocks. This was not a factor above Mach 1.4.[193]

The variable-contour nozzle employed flexible, steel upper and lower walls that could be jacked at multiple places to match interchangeable contour templates, and then locked in place. Since this was a converging-diverging nozzle, the several contours actually extended through the test section itself, causing the variation in test section height. The nozzle's side walls were fixed at the same 54 inches of the test section. The nozzle design range was from Mach 1.25 to 2.2, with any speed within that range possible, but calibrated templates were made only for Mach numbers 1.4, 1.6, 1.8, and 2.0.[194]

The tunnel was designed to operate at pressures ranging from 0.125 to 2.5 atmospheres (1.8 to 36.7 psia), though it normally operated between 0.25 and 2 atmospheres. Pressure was controlled by dampers at the settling chamber. Compressed air, stored on site at 110 psi and dried to a dewpoint of –70°F, was used to pressurize the tunnel. During test runs at low pressure, a small amount of this air was continuously bled into the tunnel to maintain an overall dewpoint low enough to prevent condensation. This was frequently –30°F or below for high-altitude simulations.[195]

The typical stagnation temperature was 110°F. Compression heat was removed by cooling coils installed at turn 3, downstream from the compressor. A 7,000-gallon-per-minute water flow through the coils reduced the temperature of the air from the compressor about 200 degrees. An external heat exchanger transferred the water's heat to the atmosphere.[196]

The 4-Foot SPT's main drive was a 7-stage, axial-flow compressor located just after corner 2. Turning at 1,300 revolutions per minute, the unit delivered 870,000 cubic feet of air per minute at a 2:1 compression ratio. This required a 6,000-horsepower electric motor, but the original drive was replaced with two electric motors totaling 45,000 horsepower in 1950 to allow a wider range of speed-pressure combinations. Both original and replacement motors had a service speed of 800 revolutions per minute, so a gearbox was needed to increase the rotational speed. The motors and gearbox were housed in a room extending west from the tunnel's southwest corner. The motors were

variable-speed motors, but not for airspeed control. Heavy rotating machinery, such as this drive system, must be brought up to speed and stopped slowly to avoid damage, and this helps establish a stable flow in the tunnel as well. The drive shaft penetrated the tunnel wall and corner 2 turning vanes enclosed in a fairing that expanded into the compressor's inner wall. It and the outer wall tapered to steadily reduce the annular volume between them, which, along with stationary blades between each pair of rotating ones, compressed the air as it moved through the unit. Both the rotating and stationary blades had an airfoil shape. The rotor acted to move the air, and the stator, with blades pitched in the opposite direction, provided the compression. To help stabilize the flow, the compressor's inner wall tapered to a point as it extended further down the long return leg.[197]

HISTORY

Well before World War II, aeronautical researchers had begun to contemplate the idea of supersonic flight, and they had made some progress in understanding how an airplane might perform while flying faster than the speed of sound. Those studying the problem, including engineers like John Stack and Eastman Jacobs at Langley, had realized since their experiments in the 11-Inch High-Speed Tunnel that the so-called "compressibility burble," to use Stack's term, and its associated shock waves changed aerodynamics significantly at Mach 1. But whether an aircraft could safely penetrate what the popular press incorrectly dubbed the "sound barrier," and how much faster than Mach 1 might be possible, was unknown. By the time the war neared its end, the English and German jet engines and the latter's V-2 missiles had convinced American aircraft designers and researchers that supersonic flight was not only possible, but likely in the near future.

Langley's John Becker, Stack's assistant division chief, had managed to obtain funding to build small supersonic and hypersonic tunnels during the war, but by the end of the war, the need for a larger supersonic tunnel, one capable of generating conditions that realistically simulated high-altitude flight, was clear. With so much to be learned, the engineers wanted models large enough to be able to accommodate not only strain gages to measure forces, but also a large number of pressure taps and servo-driven flight control surfaces. The test section would need to be considerably larger than the models so that shock waves from the model that would be reflected off the walls did not strike the models. An intermittent, blow-down tunnel like the Germans had used offered the easiest solution, but such a tunnel was necessarily small in cross section, and run times were short. Researchers really wanted a tunnel that could operate continuously. Taken together, these requirements presented a tall order for tunnel designers, but conceptual studies indicated a tunnel having a cross section of about 16 square feet could be done within a budget that might be approved. Assuming that the highest speeds would be required only at low pressure meant that a 6,000-horsepower drive would suffice.[198]

Congress authorized Langley's request for $900,000 in February 1945, and design began in earnest. Donald D. Baals and Kent Horton led the design team, but they sought

help for one of the project's toughest challenges, the compressor. Axial-compressor technology was relatively unknown in 1945, and while one resembled a steam turbine turned backward, using such a machine as a compressor instead of expander (turbine) presented its own challenges. The analytical portion of the project was formidable, but two engineers at the 16-Foot High-Speed Tunnel, M. F. Miller and J. F. Runckel, took on the task. Miller and Runckel developed the aeronautical design, including the overall arrangement, size, and blade configurations. Given the demanding physical specifications for such a machine, Langley contracted its fabrication to turbine and heavy-rotating-equipment manufacturer Allis-Chalmers.

The fabrication and erection schedule initially went well, and major sections began to arrive at Langley in fall 1945, but that did not last. The United Auto Workers Local 248 voted to strike Allis-Chalmers's West Allis, Wisconsin, plant, the factory making the compressor, in April 1946. Part of a broader union effort to recoup what organized labor saw as "lost ground" during World War II, the Allis-Chalmers strike lasted much longer than those by other unions elsewhere, a total of 329 days. This strike had a devastating effect on the schedule for the 4-Foot SPT, delaying its completion nearly two years. The tunnel finally opened in May 1948.[199]

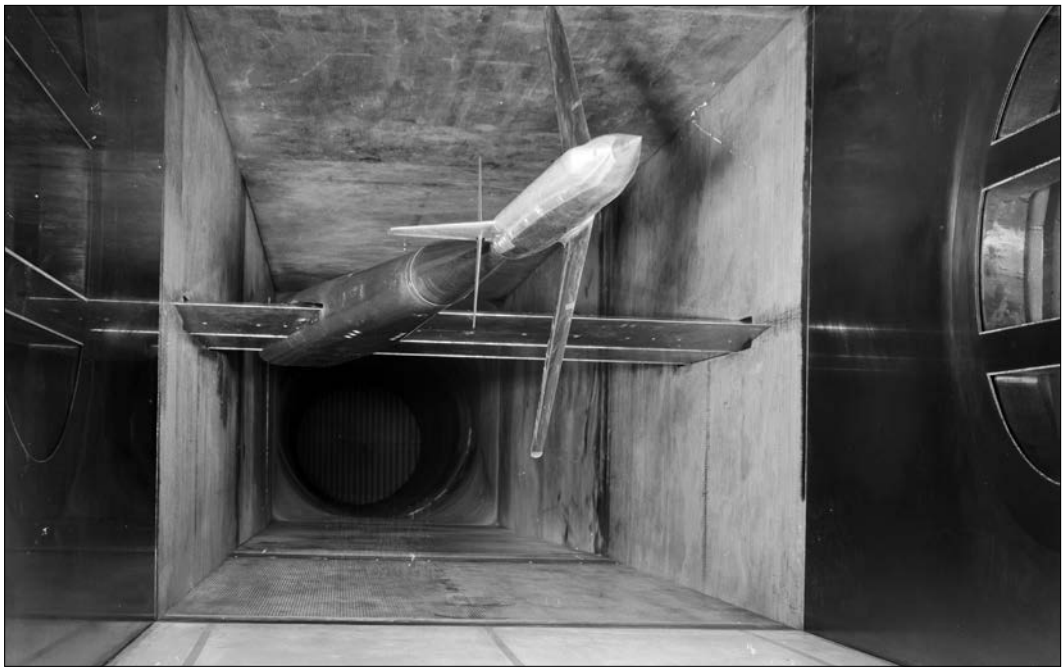
Once online, the tunnel was rapidly booked solid for tests by every American aircraft manufacturer building supersonic jet planes. Virtually every new military jet, including the "Century Series" fighters; B-58 bomber; and most of the experimental, high-speed "X-planes" spent development time in the 4-Foot SPT, and the tunnel and its staff gained a reputation for producing reliable data quickly. As the demand for a wider range of test conditions grew, the NACA installed new drive motors that raised the power to 45,000 horsepower. For up to one-half hour, the motors could be overloaded to produce 60,000 horsepower. The power increase permitted the tunnel to produce its highest speeds at its highest pressure to simulate low-altitude supersonic flight.[200]

The 1960s saw considerable interest in the idea of a commercial supersonic transport, an idea seemingly made practical by the XB-70 test flights and the announced development of the Anglo-French Concorde, but interest in the United States was tempered by several criticisms, including the potential effects of sonic booms. This concern led to some unique testing in the 4-Foot SPT. Engineers needed data on how the several shock waves that formed around different parts of a supersonic airplane merged and propagated as their distance from the aircraft increased. To get readings on the characteristics of the shock waves some distance from the model in the 4-foot tunnel, extremely small models were needed, typically about 1 inch long. The tiny models were sting-mounted near the tunnel floor, with pressure probes located from about the tunnel's centerline to the ceiling. The sting telescoped to move the model, and its shock wave, past the pressure probes. Models so small and precise provided a challenge to Langley model makers, but they were up to the task. Similarly, the instrument shop furnished new pressure sensors capable of measuring the extremely weak shock overpressures. The tests, however, ultimately generated data that confirmed the theoretical predictions for large

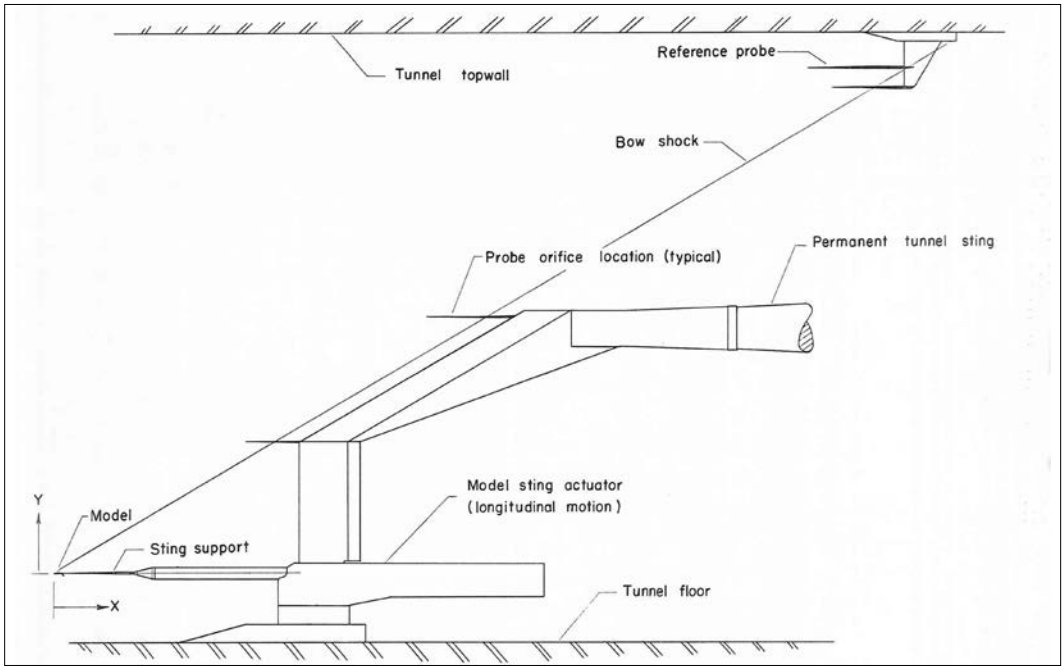
aircraft. Unfortunately, though some progress has been made, previous theories and tests did not identify shapes that reduce the boom to acceptable levels. As of 2023, NASA was revisiting this issue with its Quiet Supersonic Technology (QueSST) program. [201]

The 4-Foot SPT, the NACA's early supersonic workhorse, began to be overshadowed by other, larger supersonic tunnels during the 1950s, including several new tunnels at the Ames Laboratory in California, and perhaps most significantly by the group of Unitary Plan wind tunnels—one at each of the NACA's three laboratories, plus a dual-circuit tunnel at the Air Force's new Aircraft (later Arnold) Engineering Development Center in Tullahoma, Tennessee. Langley's Unitary Plan tunnel included two 4-foot test sections with a speed range between Mach 1.47 and 4.63. The Unitary Plan tunnels were all operational by 1956.[202]

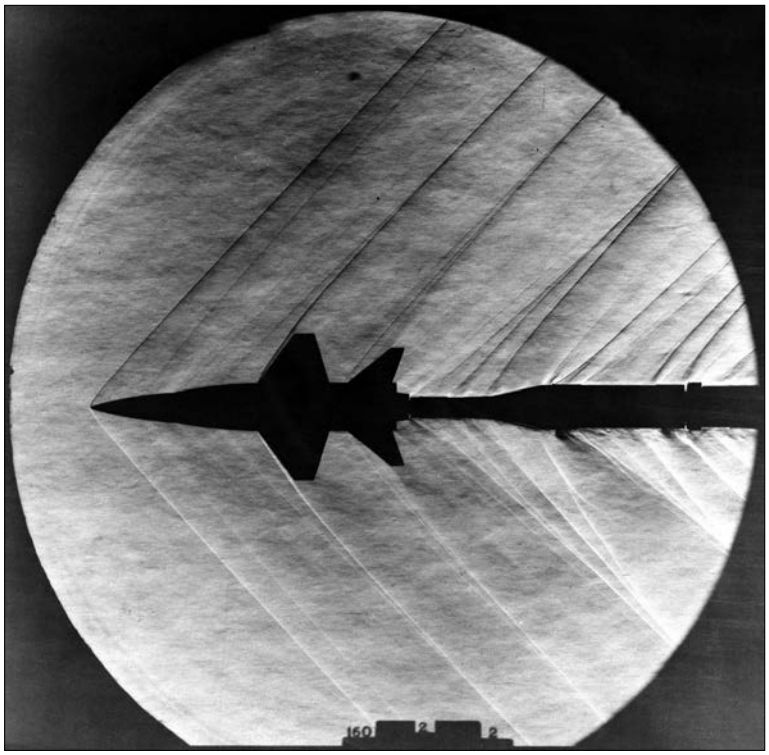
By the 1970s, emerging problems with fuel availability and cost, changes in the military's interest in ever-higher speeds, and the success of high-subsonic commercial jet airliners shifted research interests more heavily toward the transonic regime. Concepts such as Richard Whitcomb's supercritical airfoil promised economic advantages around Mach 0.9, and additional transonic research might yield additional benefits for both manufacturers and airlines. To increase its focus on transonic research, NASA decided to construct a complex wind tunnel called the National Transonic Facility (NTF) at Langley, specifically on the location of the 4-Foot SPT, even though other land was available in the West Area. Space, however, was not the only reason for the location. Some major components of the 4-Foot SPT, including its motors and cooling tower, were used in the new tunnel to reduce its cost. The cooling tower did not even have to be moved. Accordingly, the pioneering supersonic tunnel was demolished in 1977, and NTF construction quickly reconfigured the site. Some of the 4-Foot SPT's components still survive in the NTF, but others, including the motors, have since been replaced, leaving tangible evidence of the 4-Foot SPT increasingly difficult to find.[203]



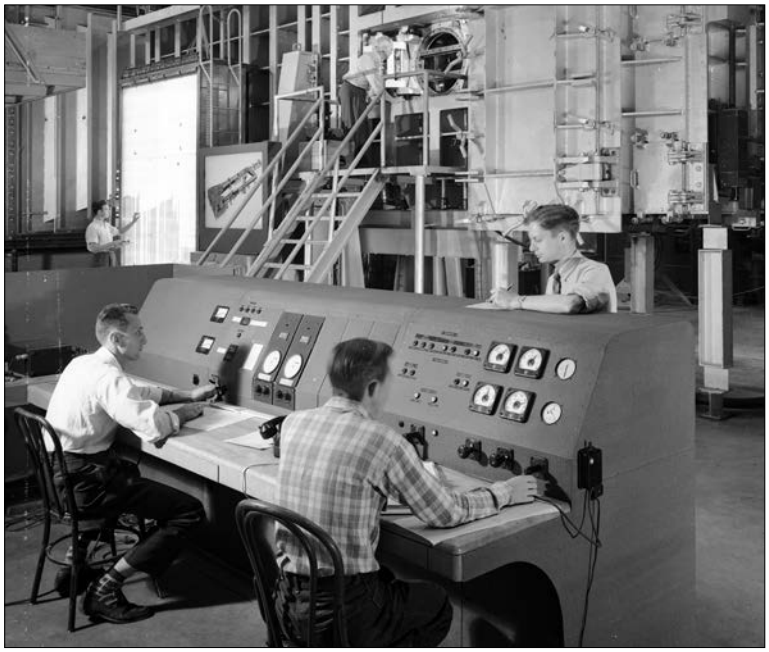
This 1940 view of the 4-Foot Supersonic Pressure Tunnel's test section shows a model mounted in a vertical orientation on the sting. The sting shifted on the horizontal strut to change the angle of attack, rotating the model about its pitch axis. The strain gage circuits measuring forces were easily adjusted to compensate for gravity, making the model's orientation irrelevant. (Photo credit: NASA LRC-1940-B701_P-62225)



This section drawing shows a test setup in the 4-Foot Supersonic Pressure Tunnel's test section. The nozzle's flexible floor and ceiling extend from the left through the test section, the circular schlieren windows, and the vertical model orientation frequently used. (Image credit: NASA TM X-889, Fig. 3)



This 1962 schlieren photograph of a North American X-15 oriented vertically in the 4-Foot SPT reveals both the nose shock and shocks off the wings and stabilizers. Weaker shocks merging into the stronger ones are also visible. The speed is Mach 2. (Photo credit: NASA LRC-1962-B701_P-02577)



The 4-Foot Supersonic Pressure Tunnel's test chamber in 1949. Note the three large manometer boards, each with multiple tubes, and the cameras set up to take photographs of them periodically for later reading. This was the standard technique before computerized data acquisition equipment became available. (Photo credit: NASA LRC-1949-B701_P-62911)

A researcher looks through a magnifying glass at one of the tiny models used in sonic boom tests in 1961. These precisely crafted models were between ¼ and 1 inch long. (Photo credit: NASA LARC-1961-B701_P-01869)

26-INCH TRANSONIC BLOWDOWN TUNNEL

Space Shuttle orbiter model in the test section of the Transonic Blowdown Tunnel in 1973. (Photo credit: NASA LRC-1973-B701_P-04123)

SIGNIFICANCE

The 26-Inch Transonic Blowdown Tunnel (TBT) was a rapid response to a pressing need for transonic testing facilities at Langley during the late 1940s and early 1950s. While not specifically intended for the role, it became one of Langley's important facilities for aeroelasticity research and flutter testing, which significantly extended its service life.

DESCRIPTION

The TBT was a blowdown tunnel powered by compressed air from the LTPT or an air reservoir served by the same compressors. The TBT's location in Building 583, next to the LTPT's Building 582-A in the East Area, made the connecting run of 24-inch-diameter pipe short and straightforward. Three 24-inch-diameter rotovalves controlled the flow to the TBT. They could be modulated as desired from a single control. After passing through the tunnel, the air exhausted to the atmosphere through a large vertical stack equipped with sound-attenuation baffles.[204]

Externally, the tunnel had a circular cross section throughout its length, which measured approximately 80 feet. It was a steel shell with external stiffening rings supported by steel bents. The settling chamber and 6-foot-diameter test section plenum were cylindrical, while the diffuser was tapered, expanding toward the stack.

The test section had an octagonal cross section with 26.4 inches between opposite walls and longitudinal slots along the dihedral angles. The slots were 7 feet long, but the useful test section length decreased from about 2 feet to 10 inches as the tunnel's speed increased. Windows in six of the sides and in the plenum allowed visual and photographic observation, including schlieren photography. Model access was through hatches in the plenum and test section. Models were supported on a sting that was mounted on a circular arc strut that could vary the angle of attack between –9 and +12 degrees. An internal strain-gage balance measured forces and moments, and additional strain gages could be mounted on larger models, especially flutter models. Pressure cells that used a beam of light to record their readings on moving film were also available. With the relatively short run times—typically 20 to 30 seconds—strip-chart recorders captured most force data. Flutter tests employed signal amplifiers and oscillographs to capture the highly dynamic data.

A variable-area orifice plate at the diffuser entrance controlled the Mach number between 0.6 and 1.45, though Mach numbers above 1.33 required bleeding air from the plenum. Once the flow choked at the orifice plate, the stagnation pressure could be raised further without a change in speed. Stagnation pressures between 1 and 5 atmospheres (14.7 and 73.5 psia) were possible.

HISTORY

By 1948, Langley engineers had succeeded in developing the first practical wind tunnel for transonic research. The slotted-wall test section had been proven, though not perfected, in the conversion of Langley's 8- and 16-Foot High-Speed Tunnels into transonic tunnels, but they exhibited some problems with humidity, turbulence, and low Reynolds numbers. Only a new tunnel, the 8-Foot Transonic Pressure Tunnel, could address all of these problems, but it had just been authorized and would not enter service until 1953.

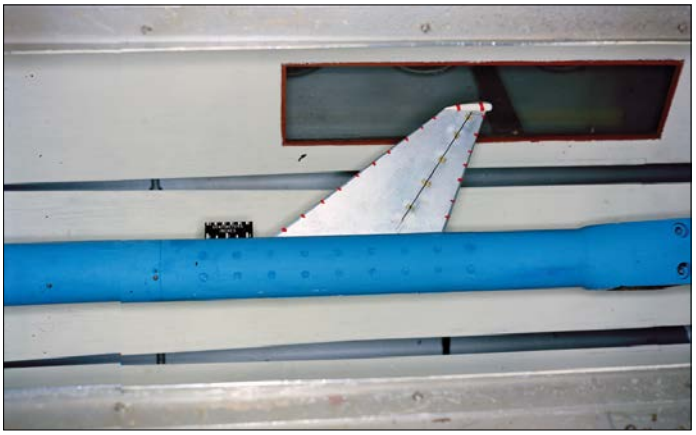
To help provide additional transonic testing capability in the interim, Albert von Doenhoff and Laurence K. "Larry" Loftin, Jr., proposed using the 150-pound-per-square-inch compressed air from the LTPT to power a small blowdown tunnel with a slotted test section. Space for such a tunnel was available next to the LTPT in Building 583, so the piping connection would be simple.

As with all parasite tunnels, the final design for the TBT was a compromise that involved trade-offs between size, speed, and run time. Von Doenhoff and Loftin emulated the 8- and 16-foot tunnels by designing an octagonal test section with slots where the walls met. The tunnel's settling chamber and diffuser were necessarily short to fit the available space, and the plenum provided only a cramped space for installing and adjusting models. But the TBT was easy and inexpensive to build, and it opened in October 1950. Models for it, being similarly small in size, were also inexpensive to build, with plastic becoming the preferred material for fuselages. Wings and tail components were generally steel to cope with the high dynamic pressures possible. Typical models measured 10 inches long with wingspans no greater than 7 inches, since anything larger would be struck by reflected shocks.[205]

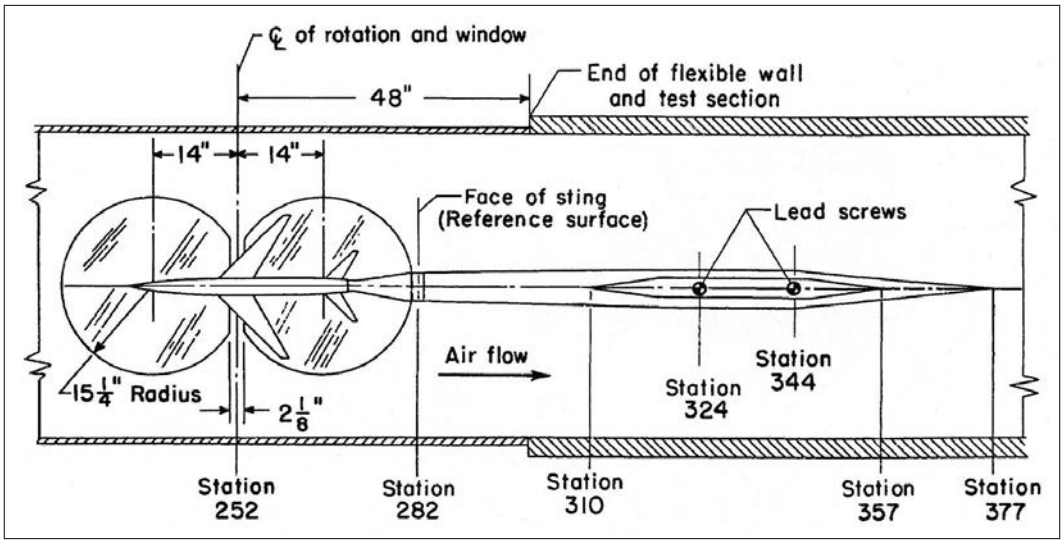
About 1951, the TBT began to take on a new role when researchers began doing flutter, or aeroelasticity, testing in it. Flutter tests are distinctly different from conventional aerodynamic testing because they involve the way aerodynamic forces cause the aircraft's structure to flex. Aircraft structures must be strong, but light as well, and this means they will be relatively flexible. All materials are elastic to some degree, and the stiffness of a part or assembly is strongly affected by its shape as well. Every part or assembly will have certain resonant frequencies, too, and an excitation force at that frequency will cause a sympathetic vibration that can get out of control. Long, thin items such as wings will flex both in bending and in torsion, and if both modes are resonant at similar frequencies, they can work together to cause catastrophic failures, sometimes within seconds. Aeroelasticity testing identifies design and operating conditions that can cause damaging flutter to occur. Researchers began doing flutter tests in the TBT because the aerodynamic forces that can cause it peak around Mach 1. Like other aspects of transonic flight, transonic flutter was not well understood, so gaining knowledge of it was crucial to the development of jet aircraft during the 1950s.

While the TBT looked to be well suited for flutter research, it was necessary to compare its data with those obtained in free-flight drop tests, and an early test program found excellent correlation between the two. With this confirmation, the TBT hosted many flutter test programs over the next decade. Even after the Transonic Dynamics Tunnel, which was designed specifically for aeroelasticity research, went into service in 1960, researchers continued to use the economical TBT for a variety of flutter research projects for more than a decade.[206]

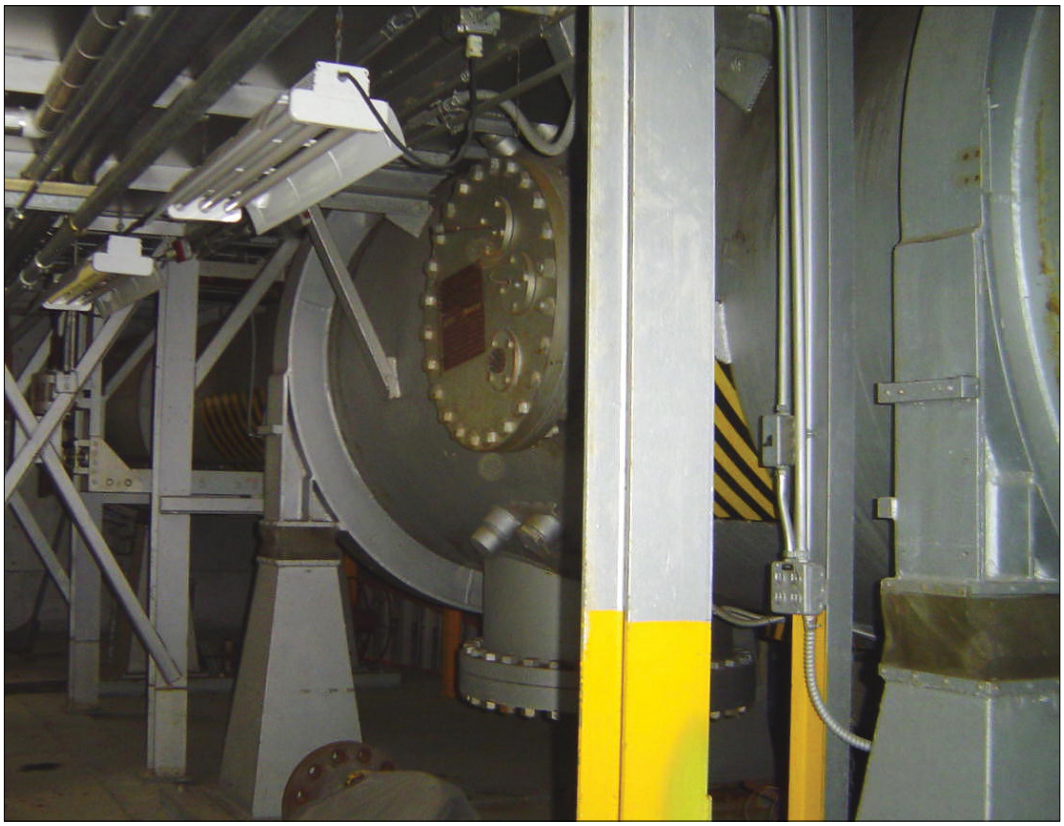
Although the exact date is unknown, the TBT was deactivated during the 1970s. Since another blowdown tunnel in Building 583 was built directly above the TBT and used the same air system, the TBT remained in place and essentially intact, including its connections to the LTPT and exhaust stack, until Building 583 was demolished in October 2014.



F-111 Vertical Tail Trend Modeling in the Transonic Blowdown Tunnel in 1966. (Photo credit: NASA LRC-1966-B701_P-02366)



This sketch shows the general arrangement of the Transonic Blowdown Tunnel. Not shown is its connection to the Low-Turbulence Pressure Tunnel near the right end. Note how the 20-Inch Variable Supersonic Tunnel (later rebuilt into the 6- by 28-Inch Transonic Tunnel) was mounted above, and connected to, the TBT so that it could use the same air source and exhaust stack. (Image credit: NASA TM X-1130)



This view of the Transonic Blowdown Tunnel, looking downstream toward the exhaust stack (not visible in the shadow), shows the test section plenum with its circular hatches for test section access. The settling chamber is out of sight to the right. (Photo credit: J. Lawrence Lee)

HYPERSONIC FACILITIES COMPLEX

This 1989 aerial view of the Hypersonic Facilities Complex, looking northwest, shows the concrete west (left) and east (right) wings flanking the brick central office building. The vacuum spheres and some of the vacuum pipes are clearly visible from overhead. Visible behind the largest sphere is the Scramjet Test Complex, which operates one tunnel located in the HFC. (Photo credit: NASA LRC-1989-B701_P-11045)

SIGNIFICANCE

The Hypersonic Facilities Complex (HFC), originally named the Gas Dynamics Laboratory (GDL), was the NACA's earliest installation with multiple hypersonic wind tunnels. The various tunnels utilized air and, later, specific gasses, particularly helium and nitrogen, to investigate aerodynamic and aerothermodynamic problems in flight regimes above the speed range of Mach 5. The facility's core tunnels have been blowdown-type tunnels powered by common differential-pressure systems.

Designed to be flexible and adaptable, the HFC has seen numerous modifications and managerial reorganizations since its opening in 1951, and it remains one of NASA's premier resources for very-high-speed and spacecraft reentry studies.

DESCRIPTION

The HFC, Building 1247 in Langley's West Area, is a U-shaped structure of brick and concrete. The central portion of its southeast face is a 3-story brick office building with a concrete portal surrounding its central entrance. This central portion is flanked by two concrete wings extending in a northwesterly direction. The "east wing" (Building 1247-D) contains rooms and test cells housing most of the laboratory's tunnels that use air. The "west wing" (Building 1247-B) historically housed the helium and nitrogen tunnels, although some air-based tunnels are located in this wing as well. Both wings feature central halls with test cells on each side, though their plans differ in size and proportion. The East Wing is the larger of the two, and it features a wider central hall.

A partial second floor in the East Wing contains a central control room that manages air distribution to all blowdown tunnels in the wing.

Reinforced concrete construction was used in the two wings of test cells as a precaution against the very high pressures and temperatures required for hypersonic blowdown tunnels. Heavy steel doors with equally heavy hardware open from each test cell onto the central hall. Each test cell has floor and wall penetrations for air/gas supply and vacuum pipes to suit the requirements of its specific tunnel.

Visually, the HFC is dominated by five large, steel vacuum spheres, four 60-foot-diameter spheres along the southwest side, and a 100-foot-diameter, ribbed sphere between the two wings. These are supplemented by several other, smaller vacuum spheres between the wings. Large-diameter steel pipes, which are exposed to the extent practical, connect these spheres to the tunnels and vacuum pumps inside the structure. Through the use of large valves, many of the tunnel-sphere connection configurations can be changed to suit the nature and required run time of each test.

Room B-104 in the West Wing contains equipment for handling and reclaiming helium. Following a run in any of the helium tunnels, this equipment pumps the helium from the vacuum sphere(s), filters it, and compresses it to 5,000 psi for storage in an on-site rack of high-pressure bottles. From there, helium can be routed to any of the helium tunnels when needed, though only one can be run at a time.

The open area partially surrounded by the building and extending toward the northwest contains three of the large vacuum spheres, a cooling tower, racks of high-pressure gas bottles, and vacuum pumps for the air system. Water circulated through the cooling tower is used to cool the hot air or gas leaving many of the tunnels and, thus, improve the efficiency of the vacuum spheres.

HISTORY

The original GDL was part of the large investment Congress made in NACA facilities during the late 1940s and early 1950s to support high-speed-flight research. Wind tunnels for the supersonic and transonic flight regimes were conventional, closed-circuit tunnels. Large, powerful, and expensive, the new tunnels, particularly the Unitary Plan Wind Tunnels, for speeds of up to about Mach 4.5, generally resembled their subsonic predecessors, even though their test sections incorporated key new features and their drive power increased dramatically. Wind tunnels for speeds in the hypersonic range (Mach 5 and higher) presented conditions too extreme to achieve with this design. As in supersonic tunnels, converging-diverging nozzles can be designed to produce hypersonic speeds, but the high pressure and temperature differentials involved mean that the chemical and physical properties of the test gas must be considered. Hypersonic nozzles typically have exit-to-throat ratios on the order of 20–30 to 1. Most gasses, including air, will liquefy leaving the throat of such nozzles, thanks to a drastic drop in temperature. To prevent liquefaction, the gas must be heated to 1,000°F, or more, before it enters the nozzle. This means that most nozzles need to be cooled to prevent distortion and

degradation. Similarly, high pressures, often above 1,000 psi, are necessary to achieve the proper mass flow through the nozzle. Such extremes dictated a facility unlike any other at Langley.[207]

Langley's 11-Inch Hypersonic Tunnel, opened in 1947, had shown that much could be learned from short test runs, but it also demonstrated how hypersonic tunnels had to be carefully designed for a given speed. The nozzle requirements, and their concurrent pressure and temperature demands, were too exacting to allow the use of flexible walls to vary test speeds. While it was theoretically possible to design a hypersonic tunnel with sufficient compressors to achieve continuous operation, the power and expense made that an impractical choice, so engineers decided to pursue blowdown-type tunnels. These could use reasonably sized compressors to compress air, or any other gas, over time; similarly, vacuum pumps could evacuate vacuum vessels in advance of test runs. With quick-acting valves, rapid-responding instrumentation, and careful management, two or more test runs might be possible from a single preparation cycle.

John Stack, the indomitable head of Langley's Compressibility Research Division, championed the idea of a facility that had a common gas system with a large, pressurized sphere serving several blowdown tunnels. Each tunnel would be designed to different specifications so that they complemented one another, giving the facility a wide range of testing capabilities. Antonio Ferri, an Italian researcher who had joined Stack's staff after World War II and had experience with high-speed blowdown facilities in Europe, agreed in principle, but Ferri and engineer Macon C. Ellis took the idea a step further. They replaced the single, large pressure sphere with a rack of small-diameter bottles capable of holding air at a much higher pressure, as much as 5,000 psi (borrowing a technique that had worked well aboard submarines). They then converted Stack's big sphere into a vacuum vessel. Connecting tunnels between the two would yield the highest possible differential pressure across the tunnels' nozzles.[208]

This multi-tunnel concept for the GDL received approval from Congress in 1949. At $5.5 million, its initial cost was more than twice that of any other facility at Langley, though the price tag for Langley's Unitary Plan Tunnel, approved later the same year, would triple that staggering figure. During these early years of the Cold War—the Soviet Union detonated its first atomic bomb in 1949—Congress was in the mood to maximize America's investment in aeronautical research and, thus, ensure its strength in high-speed aviation and the emerging field of guided missiles.

At its opening in 1951, the GDL housed several supersonic and hypersonic blow-down tunnels using air and helium to cover speeds ranging from Mach 1.5 to Mach 18. Ferri and Ellis, with design assistance from Clinton Brown, developed their ideas into a complex, but flexible and practical distribution system for dried air and helium that serviced test cells arranged in two wings around a central office building. The test sections for these tunnels all measured about 20 inches, a size that allowed reasonably sized models and nozzle dimensions that were practical to machine and operate. A bottle rack held 19,000 cubic feet of air at 5,000 psi. Routing this air through one of the

tunnels and then to a vacuum sphere caused pressure ratios across the nozzle as high as 10,000 to 1. Steam and electric heaters raised the temperature of the supply air to approximately 1,100°F to prevent liquefaction, and a cooling system furnished water to cool both the nozzles and the tunnels' exhaust flows. Steam ejectors lowered the pressure in the vacuum spheres. A similar system handled helium, but it included vacuum pumps, purification equipment, and a compressor to recover the helium for reuse. Given the unknowns and extreme conditions of hypersonic research, the engineers specified reinforced-concrete test cells to enclose the various tunnels and prevent an accident in one from affecting the others. This basic design has been maintained to this day in spite of numerous changes to the facility's tunnels.[209]

Many of the problems tackled by GDL researchers in the facility's early years involved conditions that would be experienced by guided missiles, especially by nuclear warheads reentering the atmosphere on the downward side of their ballistic trajectories. At Mach 5–10, the problems involved not only aerodynamic stability, but also searing heat generated by both air friction in the boundary layer and the high compression in shock waves. Finding designs that minimized the heat exposure while maintaining a predictable flight path and materials that could withstand temperatures of more than 2,000°F quickly became interrelated problems that NACA researchers tackled at both Ames and Langley.[210]

In the midst of this boom in research, the preferred method of hypersonic research became something of a controversy within the NACA. The Pilotless Aircraft Research Division (PARD) had been established at Wallops Island, Virginia, during World War II as a site for launching small rockets that could boost model airplanes to speeds and altitudes in free flight that could not then be duplicated in Langley's wind tunnels. By the time the GDL opened, Langley had closed the gap considerably, but researchers at Wallops argued that the technology they had developed produced superior data, especially as speeds approached Mach 10. The NACA appointed an ad hoc committee consisting of Clinton Brown from Compressibility Research, Charles Zimmerman from Stability and Control, and William O'Sullivan from PARD to investigate and make recommendations. Their findings were mixed. While acknowledging that PARD's methods were better at generating the high temperatures desired, Langley's (and Ames's) hypersonic tunnels could do most of the research and development work at a lower cost. Flight testing was necessary, but more cost-effective for final testing of developed hardware.[211]

Blowdown tunnels offered something else for researchers that PARD flights could not provide: the ability to test with gasses other than air. Helium was particularly attractive because it does not liquefy until its temperature reaches –452°F, only a few degrees above absolute zero, making heating unnecessary up to about Mach 25, and reasonable heat permits speeds as high as Mach 40, beyond what PARD flights could achieve. With the proper equipment, helium could be highly purified and reused, thus eliminating problems stemming from water and most other contaminants. Helium did,

however, have some disadvantages. A minor one was that the speed of sound (Mach 1) in helium is almost three times that in air at the same temperature. Much more problematic were its properties at high temperatures. At elevated temperatures, helium, a monatomic gas, had different thermodynamic properties than air, which is composed mostly of diatomic molecules, and the required corrections were not well understood in the early 1950s. Langley researchers have also used other gasses, including nitrogen and tetrafluoromethane (CF_4), in some of the renamed HFC's tunnels to reduce operating problems and improve their understanding of gas behavior under extreme conditions.

Research operations and equipment assignments in the HFC have changed many times since its opening, and its tunnels have been removed, installed, modified, and relocated in a bewildering manner, but it is the intelligent initial design of such a flexible facility that has made these alterations to meet changing needs possible. Compared to the cost of new construction that might otherwise be needed to accommodate new tunnels, the savings to NASA, though difficult to estimate, have been, and continue to be, enormous.

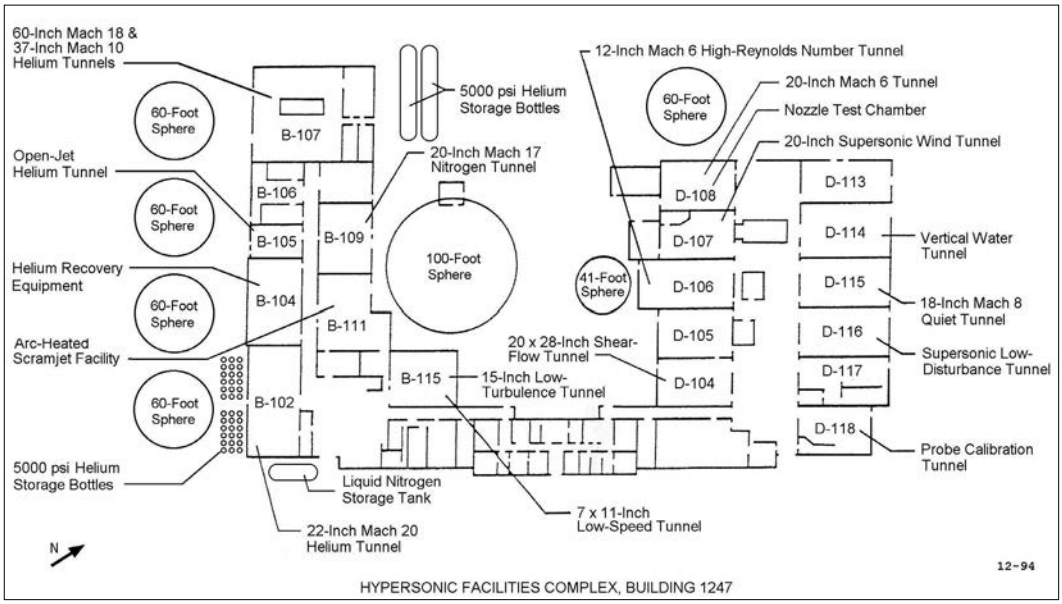
Tunnels in the Hypersonic Facilities Complex

The HFC, intentionally designed for flexibility, has housed numerous wind tunnels during its life. Some of these remain in service, while others have been dismantled or modified. Not all of them are hypersonic tunnels, since some space often has been available for other research, and slower tunnels have frequently occupied some rooms. In certain cases, the information available about a particular tunnel is imprecise or unavailable, but the primary tunnels that have been, or remain, in the HFC are briefly described below. For clarity, these will be presented in room-number order rather than chronological order. Only rooms (test cells) with aerodynamic tunnels are shown. Facilities intended primarily for studies in fields such as magnetoplasmadynamics, materials, and acoustics are not included. The HFC also has hosted a number of small, "tabletop" hypersonic tunnels over the years, but records about them are scarce, and these devices are not included.

In the context of hypersonic tunnels, a "conventional" tunnel is a blowdown tunnel, whether the inlet gas is heated or unheated, that is capable of test runs at least several seconds long. "Shock," "impulse," "expansion tube," and "hotshot" all refer to facilities that utilize sudden, essentially explosive, driving forces to produce ultra-high-speed test flows lasting only fractions of a second.

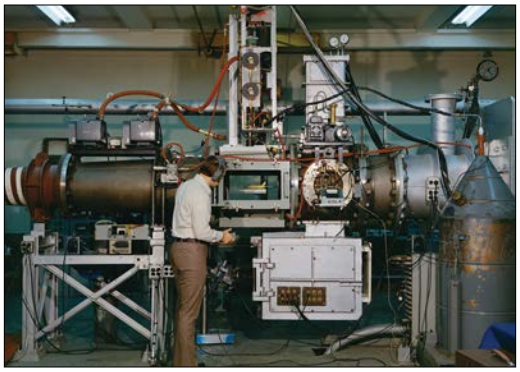
Many of these tunnels have had multiple names, both official and unofficial, over the years, with no uniform naming rationale apparent. The primary names shown here are those that appear to be the most consistent and recent, with the known alternate names indicated in the text.[212]

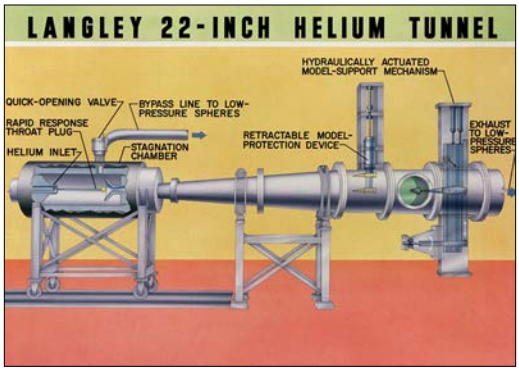
This winter 1969 view, complete with a dusting of snow, illustrates how the large vacuum spheres dominate the Hypersonic Facilities Complex. They are 41, 60, and 100 feet in diameter. Spheres were used because their double-curved surfaces strongly resist buckling inward, making them the most structurally efficient shape for large vacuum vessels. (Photo credit: NASA LRC-1969-B701_P-02164)



This drawing shows the wide variety of facilities Building 1247 housed in 1994. The Hypersonic Facilities Complex was designed to be adaptable to changing needs, and many of its research facilities were changed between 1951 and 1994. (Some did not involve hypersonic research.) Additional changes have been made since 1994, but the basic floor plan has remained the same. (Image credit: NASA drawing)

B102: 22-Inch Helium Tunnel

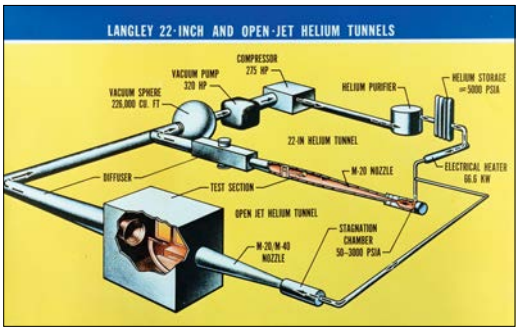




The 22-Inch Mach 20 Helium Tunnel in Room B102, 1973 photo (left) and drawing (right). Three interchangeable nozzles produced speeds of Mach 18, 22, and 26, with the Mach 22 nozzle used the most. The model-protection device shielded the model from potentially damaging transients during startups. (Credits: NASA LRC-1973-B701_P-02148 and NASA LRC-1963-B701_P-05233)

This conventional tunnel, opened in 1960, was originally named the Hypersonic Helium Tunnel. Three axisymmetric nozzles for it were built to deliver Mach 18, 22, and 26 flows, but only the Mach 22 nozzle has been calibrated, and it has been the one most-frequently utilized. The test section measured 22.5 inches in diameter, which provided a core test region between 8 and 10 inches in diameter. Helium was supplied from high-pressure bottles and exhausted into one or more vacuum spheres. A hydraulically actuated mechanism inserted a model into the stabilized flow, and a second, similar device did the same for a shield that protected the model from start-up transients or debris. The flow was established by opening quick-acting valves and stabilized with a quick-response nozzle-throat plug. Helium was recovered from the vacuum sphere after a test for reuse. This tunnel's primary modification involved the addition of a second circuit featuring a larger test chamber known as the Open-Jet Leg. The original circuit, then referred to as the Aerodynamic Leg, remained in service until being closed about 2003. It was demolished about 2007.[213]

B105: Hypersonic Helium Tunnel Open-Jet Leg

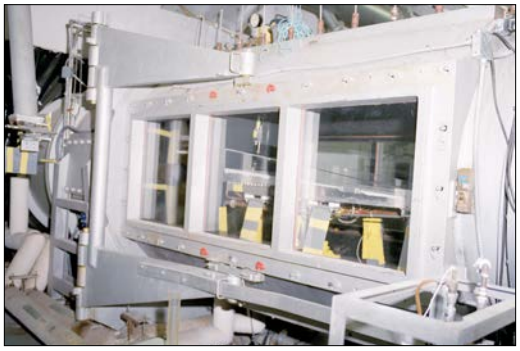


The Mach 20/40 Helium Open-Jet Leg in Room B105, showing its connection to the 22-Inch Mach 20 Helium Tunnel in B102 in 1973. The two legs utilized a common helium system, so only one leg could operate at a time. The Open-Jet Leg utilized two interchangeable nozzles. (Image credit: NASA LRC-1973-B701_P-02584)

The Open-Jet Leg was an addition to the 22-Inch Helium Tunnel that opened in 1969. It utilized two axisymmetric nozzles, one that produced Mach 20 flow at its 22-inch exit and a second that generated Mach 40 flow at its 36-inch exit. Either discharged into a larger test section, where a model-injection device swung the model into the flow

centerline after steady flow had been established. The support mechanism allowed the angle of attack to vary ±20 degrees. As with the Aerodynamic Leg, heat was not required to prevent liquefaction during Mach 20 tests, but it was needed for those at Mach 40. Run time was approximately 20 seconds. With a declining interest in hypersonic research and budgetary constraints during the 1990s, NASA decided to close this tunnel and subsequently demolish it about 1998. A commercially manufactured, skid-mounted tunnel known as the 7- by 11-Inch Low-Speed Tunnel currently occupies this space.[214]

B107: 60-Inch Mach 18 Helium Tunnel



This 1997 view shows the test section of the 60-Inch Mach 18 Helium Tunnel in Room B107. (Photo credit: NASA LRC-1997-B701_P-00680)

One of the facility's original tunnels, this conventional tunnel, also known as the Mach 20 High-Reynolds Number Helium Tunnel and as one of the Hypersonic Aeroelasticity Tunnels, opened in 1952 as the NACA's largest helium tunnel. It featured axisymmetric nozzles for Mach 16.5 and Mach 18 using gas supplied by the building's 5,000-pound-per-square-inch helium system and recovered from the 60-foot-diameter vacuum spheres on the building's southwest side. Most runs involved the use of two spheres and lasted 5–10 seconds. Models were sting- or strut-mounted with a variable angle-of-attack adjustment. An electron-bombardment system for flow visualization was available, as was a spark schlieren photography system. Ambient temperatures were adequate to avoid helium liquefaction for tests in this Mach range. This 60-inch tunnel shared the test chamber and a control room with a similar 37-inch tunnel. Much of the research performed here, especially during its later years, involved turbulent boundary layers. With a declining interest in hypersonic research and budgetary constraints during the 1990s, NASA decided to demolish this tunnel in 1998.[215]

B107: 37-Inch Mach 10 Helium Tunnel

Also known as the Mach 10 High-Reynolds Number Helium Tunnel and as one of the Hypersonic Aeroelasticity Tunnels, this tunnel opened in 1952. It was essentially a smaller, slower version of its 60-inch sibling, and it operated in the same manner using the same helium system, so only one of these tunnels could operate at a time. The two tunnel circuits shared a common control room. This tunnel ceased operations in the late 1970s, and it was demolished along with the 60-inch circuit in 1998.[216]

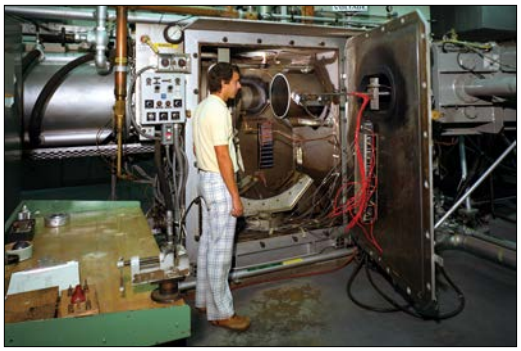
H107: 2- by 3-Foot Low-Boundary-Layer Tunnel

The unusually long test section and multiple observation windows of the 2- by 3-Foot Low-Boundary-Layer Tunnel in Room H107 are apparent in this 1999 photograph. (Photo credit: NASA LRC-1999-B701_P-00109)

This atmospheric, closed-circuit tunnel was installed as part of a modification to room H107 in Building 1247's west wing. (Room B107 had been re-designated H107 during a prior modification to the space.) When originally installed in this room, it was oriented in a north-south direction, and it shared the space with the 60- and 37-inch helium tunnels until those tunnels were demolished. In 1997, Langley considered relocating it to an extension of Building 1214, which housed the Basic Aerodynamics Research Tunnel (BART), but rejected that option, even though the two tunnels performed similar work. Instead, the tunnel underwent a major rehabilitation during 2004 that rotated it 90 degrees to better fit in the H107 space.

The tunnel is a self-contained device capable of speeds of up to approximately 100 mph, and it incorporates a honeycomb, four screens, and a 10-to-1 contraction ratio to reduce turbulence. The floor and ceiling of the 20-foot-long test section are adjustable to allow operators to set a desired longitudinal pressure gradient. Additionally, the tunnel included acoustic equipment upstream and downstream of the test section to excite the flow as needed.[217] The tunnel remains active.

B109: 20-Inch Mach 17 Nitrogen Tunnel

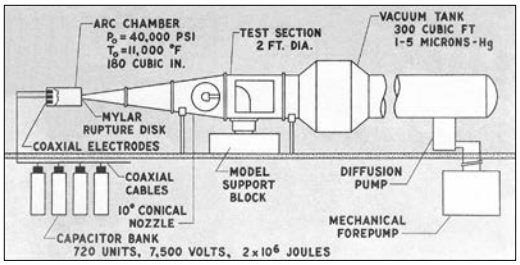


This 1977 photo of the test section of the 20-Inch Mach 17 Nitrogen Tunnel in Room B109 provides a sense of its size and operation. (Photo credit: NASA LRC-1977-B701_P-06760)

Previously known as the Hypersonic Nitrogen Tunnel, this conventional tunnel was built in 1964. Nitrogen gas, flashed from a liquid storage tank, passed through an electric resistance heater at the nozzle's inlet, continued through the tunnel's axisymmetric nozzle and test section, and exited it through a diffuser and aftercooler into a vacuum sphere. Because of the benign nature of nitrogen and its low cost, the gas was vented to

atmosphere after test runs and not recovered. Despite its name, the tunnel's test section was shown as being only 17 inches in diameter in Langley facility documents, though it may originally have had a larger test chamber and on open jet. This nitrogen tunnel was built to investigate how well a single gas could simulate air at hypersonic flight speeds. Unfortunately, the flow in this tunnel was more turbulent than desired, and the cost to rectify the flow problems could not be justified since testing with nitrogen offered no clear advantages over testing with air. With a declining interest in hypersonic research and budgetary constraints during the 1990s, NASA decided to close this tunnel about 1998 and subsequently demolished it in 2007.[218]

B115: Hotshot Tunnel



Elevation view of the Hotshot Tunnel in Room B115, which utilized an electric arc to initiate its brief Mach 20 flow. It was Langley's first hotshot tunnel. (Image credit: NASA TN D-3278, Fig. 1)

The Hotshot Tunnel, built in 1960 and operational in November 1962, was an arc-heated impulse tunnel. Since it was Langley's first hotshot tunnel, setup and calibration proved arduous, with difficult problems to be solved in materials electrodes, insulators, connections, and instrumentation. It was built primarily to perform force, pressure-distribution, and heat-transfer tests at Mach 20 and above.

As with all hotshot tunnels, this tunnel operated by heating its test gas (air, nitrogen, or helium) in a small chamber at one end with an electric arc. A bank of 720 capacitors delivered an instantaneous 7,500-volt, 2×10^6-joule potential across two electrodes in the chamber, and the arc created heated the gas to about 5,000°F, which, in turn, caused the gas pressure to increase to approximately 10,000 psi. This pressure burst a polyethylene terephthalate diaphragm and allowed the gas to accelerate through an asymmetric nozzle and pass through the test section into a 200-cubic-foot dump tank. Prior to the run, the entire tunnel downstream of the diaphragm had been evacuated to approximately 1 micron of mercury by mechanical and oil-diffusion pumps. Typical run times ranged between 30 and 120 milliseconds, which required ultra-high-speed instrumentation and control equipment. Data were recorded using high-speed oscillographs and magnetic tape.

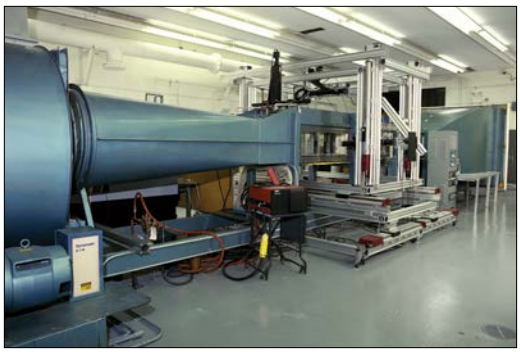
This tunnel provided Langley researchers with experience operating nonconventional tunnels, and modifications eventually allowed some tests above Mach 30. While the results were useful, the high energy involved with the arc heater continued to pose problems and risk. After an accident seriously damaged this tunnel, it was demolished in 1969. No portion of it is known to have survived.[219]

B115: 15-Inch Low-Turbulence Tunnel

The 15-Inch Low-Turbulence Tunnel in Room B115 in 1999. (Photo credit: NASA LRC-1999-B701_P-00108)

The 15-inch Low-Turbulence Tunnel is a self-contained, closed-circuit tunnel that can produce very stable air flows of up to about 88 mph. Its test section consists primarily of clear panels, and it offers excellent optical access for laser velocimetry (LV) and particle-imaging velocimetry (PIV) measurements. Recent research involving active flow control devices to improve jet engine inlet performance in adverse conditions has relied heavily on the tunnel's PIV capabilities. The tunnel remains in service.[220]

D104: 20- by 28-Inch Shear-Flow Tunnel



The 20- by 28-Inch Shear-Flow Tunnel, seen here in 1999 in Room D104. This tunnel was purchased as a package unit from Aerolab. (Photo credit: NASA LRC-1999-B701_P-00104)

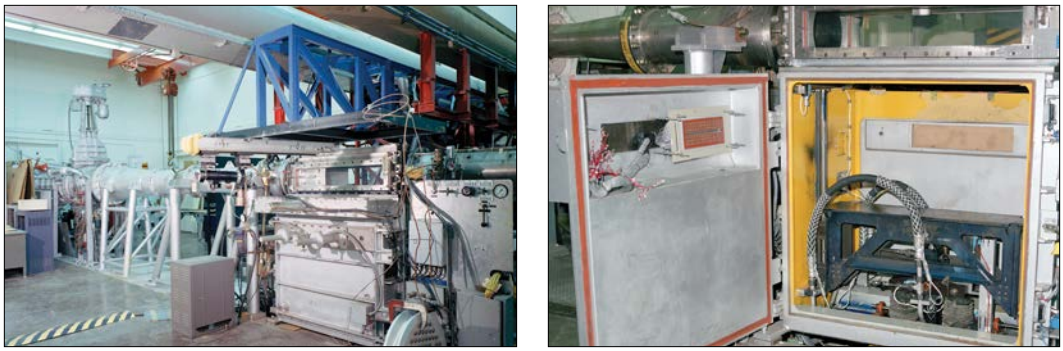
The 20- by 28-Inch Shear-Flow Tunnel is an atmospheric, open-circuit tunnel with a top speed of approximately 100 mph that was purchased as a self-contained unit from Aerolab. Intended primarily for fundamental boundary-layer research, a series of inlet screens and a large contraction ratio deliver air to the test section with very low freestream turbulence. The 15-foot-long test section features large windows on both sides and an adjustable ceiling for control of the pressure gradient through the full length of the test section. The large windows provide excellent optical access for LV and PIV measurements. This tunnel remains in service.[221]

D105: 7- by 11-Inch Low-Speed Tunnel

The 7- by 11-Inch Low-Speed Tunnel currently in Room B115, seen here in 1998. (Photo credit: NASA LRC-1998-B701_P-00457)

The 7- by 11-Inch Low-Speed Tunnel is an atmospheric, open-circuit tunnel with a top speed of approximately 100 mph that was purchased as a self-contained unit from Aerolab about 1965, initially installed in room B115, and moved into room D105 sometime later. (Room D105 earlier housed a 20-Megawatt Linear Plasma Accelerator used for magnetoplasmadynamics studies.) Initially intended as a pilot for the 14- by 22-Foot Subsonic Tunnel, it has been primarily utilized for fundamental research since 1970. It is now optimized for direct-drag measurements of flat panels, and it employs a linear air bearing drag balance. This tunnel is equipped with a variety of pitot and hotwire-type flow measurement instruments, as well as smoke-injection and smoke-wire capabilities for flow visualization. Its primary use has been for studies into drag reduction within turbulent boundary layers, but it achieved some unusual notoriety in 2008 when swimmers Michael Phelps and Natalie Coughlin made Olympic history wearing swimsuits made of a drag-reducing fabric developed in part through testing in this tunnel by Langley researcher Stephen Wilkinson. The tunnel remains in service.[222]

D106: 12-Inch Mach 6 High-Reynolds Number Tunnel



The 12-Inch Mach 6 High-Reynolds Number Tunnel in Room D106 is shown in 1982 (left) and 1995 (right). In many hypersonic tunnels, a stable flow is established before the test model is inserted to prevent damage to the model. (Photo credits: NASA LRC-1982-B701_P-08487 and NASA LRC-1995-B701_P-05012)

Also known as the Mach 6 High-Pressure Tunnel, the 12-Inch Mach 6 High-Reynolds Number Tunnel entered service in 1967. It was a conventional tunnel that used heated dry air furnished by the facility and exhausted through an aftercooler into a 41-foot-diameter vacuum sphere to generate a speed of Mach 6. Electric resistance-type heaters

heated the incoming air to a maximum temperature of about 540°F. This tunnel featured an axisymmetric nozzle into two interchangeable, 12-inch-diameter test sections. One was equipped with schlieren windows and a model-injection mechanism capable of handling models up to 4 feet long. The second test section was designed for investigations of boundary layers along the tunnel wall using a variety of measurement techniques. The tunnel was closed about 1998 and demolished in 2007 to make room for two acoustic research devices being relocated from other buildings in the West Area, the Curved-Duct Test Rig from Building 1218 and the Grazing-Flow Impedance Tube from Building 1287.[223]

D107: 20-Inch Supersonic Wind Tunnel

The 20-Inch Supersonic Wind Tunnel (SWT) was originally designed and built at the Jet Propulsion Laboratory (JPL) in Pasadena, California, in 1948, a full decade before JPL became part of NASA. At the time, JPL, a unit of the California Institute of Technology, was heavily engaged in rocket engine development, and this tunnel was one of two it built to support that activity. After JPL became a unit of NASA, its hardware role gradually shifted from rocket engines to the development of uncrewed spacecraft, drastically reducing its need for wind tunnels. By 1980, the laboratory needed the space they occupied for other facilities, so NASA looked to relocate them within the agency.

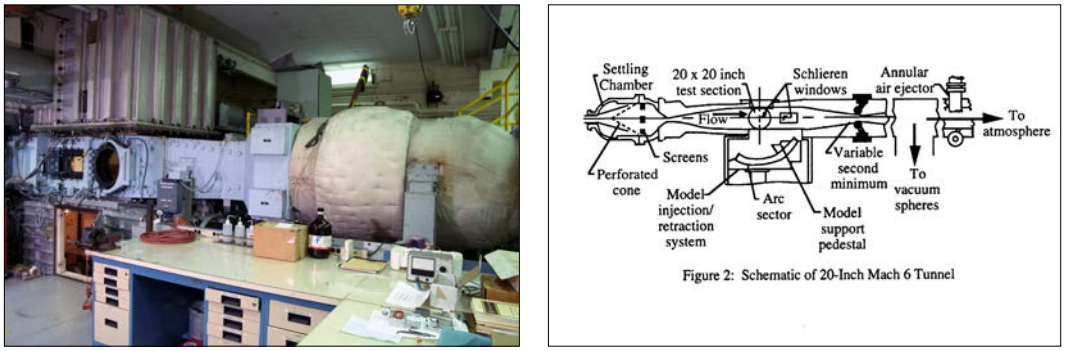
Robert L. Trimpi, a Langley researcher, realized that the 20-inch JPL tunnel could be useful at Langley, and he recommended that it be moved. Actually, only the core of the tunnel—its nozzle, test section, and diffuser—was moved to Virginia. JPL had powered the tunnels with dedicated air compressors that were not needed at the HFC, which could also furnish vacuum at the exhaust end. Between 1982 and 1986, Trimpi oversaw its move and installation in room D107. A new air-inlet section, enclosed in a room that filled part of the central hall, was built, and the diffuser exhaust was mated to a new duct with a valve that directed the flow either to atmosphere or to a 60-foot-diameter vacuum sphere. Langley named it the 20-Inch Supersonic Wind Tunnel.

Supersonic nozzles must be precisely contoured for a specific speed, but JPL engineers had designed a nozzle that used a series of jacks to flex sheets of stainless steel and, thus, recontour the nozzle for a range of speeds between Mach 1.3 and 5.6. The top and bottom surfaces were flexible, allowing both sides of the nozzle to retract for access to the nozzle and the forward portion of the test section. Both sides of the nozzle retract for access to the nozzle and the forward portion of the 20- by 18-inch test section. Trimpi added an 8-foot-diameter settling chamber, along with a "quiet" valve and flow-conditioning section to supply stable air to the nozzle and, thus, help create a uniform flow through the core of the test section.

Models are typically sting-mounted on a support that allows pitch adjustment from 34 to –9.5 degrees and ±8.5 degrees in yaw. They are protected from startup and shutdown transient temperatures and loads by a plenum isolation door and a rapid injection capability of the support system. A variety of heat-transfer and static pressure

instrumentation is available, plus laser velocimetry for flow-field measurements. In recent years, researchers developed a way for the tunnel to operate subsonically as well, and it has proven useful for airfoil testing in the Mach 0.35–0.75 range. Run times range from approximately 30 to 900 seconds, depending on conditions. The tunnel received several modifications in 1994 to improve its reliability and ease of use, including a connection to the HFC's 100-foot-diameter vacuum sphere that enables it to use the total volume of the 60- and 100-foot spheres for longer run times. The 20-Inch SWT has been a very productive facility at Langley, and it remains in active service.[224]

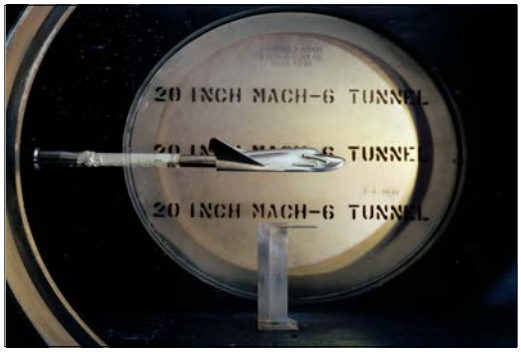
D108: 20-Inch Mach 6 Tunnel



This 1995 photo (left) and drawing (right) show the core of the 20-Inch Mach 6 Tunnel in Room D108. (Credits: NASA LRC-1995-B701_P-03545 and NASA TM-109152, Fig. 2)

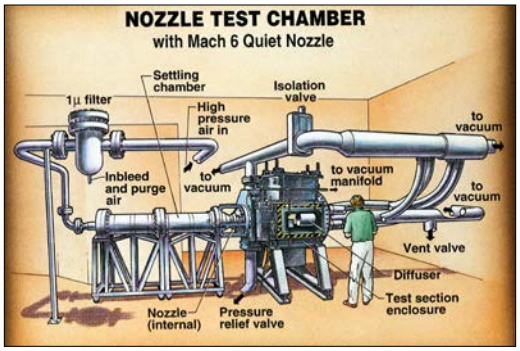
The 20-Inch Mach 6 Tunnel, opened in 1958 as the 20-Inch Hypersonic Tunnel, is a conventional tunnel utilized for aerodynamic and aerothermodynamic tests of proposed aerospace vehicles, and for the exploration of basic fluid dynamic phenomena, includ-ing boundary layer laminar-to-turbulent transition. The tunnel uses dry air furnished by the facility and heated by an electric resistance heater, and it exhausts through an aftercooler into a vacuum sphere, to the atmosphere (assisted by an air ejector), or a combination of the two. Its diffuser includes a movable second minimum. The tunnel delivers a speed of Mach 6, with stable flow in a core test area measuring 12 inches square in its 20- by 20-inch test section. Models can be fixed on the floor, or sting-mounted on an injection mechanism, which allows a pitch setting from 55 degrees to –5 degrees and a yaw range of 0 to –10 degrees. Run times vary from 2 to 20 minutes, depending on the choice of exhaust.

The results of tests conducted in this tunnel are often compared to those from tests in the 31-Inch Mach 10 and 20-Inch Mach 6 CF_4 tunnels to more fully assess the effects of compressibility and real-gas aerothermodynamics under similar Reynolds number conditions. This tunnel performed a large number of tests during the Space Shuttle development program, and it is kept available during missions to investigate potential problems. The 20-Inch Mach 6 Tunnel is still in service.[225]



A lifting body is tested in the 20-Inch Mach 6 Tunnel in 1989. (Photo credit: LRC-1989-B701_P-07581)

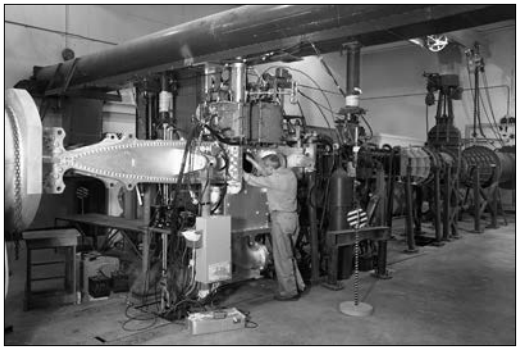
D114: Mach 6 Pilot Quiet Tunnel



The Mach 6 Pilot Quiet Tunnel (Nozzle Test Chamber) in Room D114. This tunnel was donated to Texas A&M University in 2005. (Image Credit: NSAA LRC-1993-B701_P-02631)

Also known as the Nozzle Test Chamber, this facility was not actually a research tunnel per se, but rather a conventional device used primarily to develop a low-disturbance, or quiet, hypersonic nozzle. Constructed about 1995, and originally installed in room D-108, it received heated air from the building's central system and exhausted through an aftercooler to a vacuum sphere. The extended settling chamber ahead of the asymmetric nozzle measured 85 inches long and contained as many as 11 screens, including one formed out of steel wool, to eliminate turbulence. The nozzle contraction also featured an annular slot connected to a vacuum source to remove any remaining boundary-layer immediately ahead of the throat. The 19-inch-diameter nozzle exhausted into a larger test section, where an overhead model-injection device inserted the model once stable flow had been achieved. Air exited the test section through a conical collector and diffuser to a vacuum vessel. While complex to build and operate, the apparatus achieved very-smooth, low-turbulence flow at Mach 6, and its success has prompted additional developmental work by others in the field. This tunnel was relocated to room D-114 in the late-1990s, after the removal of other equipment freed the space. After almost a decade of service, the Mach 6 Pilot Quiet Tunnel was dismantled in 2005 and donated to Texas A&M University in College Station, Texas, where it was modified and returned to service.[226]

D115: 18-Inch Mach 8 Variable-Density Tunnel



The 18-Inch Mach 8 Variable-Density Tunnel, seen here in 1961 in Room D115. (Photo credit: NASA LRC-1961-B701_P-02867)

Opened in 1960, the 18-Inch Mach 8 Variable-Density Tunnel, also known as the Mach 8 Variable-Density Hypersonic Tunnel and the 18-Inch Mach 8 Tunnel, is a conventional tunnel capable of producing a wide range of Reynolds numbers. It uses dry air heated by a two-stage heater that a control valve delivers to the settling chamber at 20 to 3,000 psi. The heater's first stage employs a circulating ethylene glycol fluid that heats the air to approximately 150°F. An electric resistance heater then raises the temperature to as high as 1,030°F. The settling chamber contains screens to stabilize the flow, which then passes through the axisymmetric nozzle and 18-inch-diameter test section. Depending on the operating pressure, the core test area measures between 4 and 14 inches in diameter. A model injection system raises the model, which can be up to 27 inches long, into the stabilized air stream. The sting has adjustments for pitch and yaw. The tunnel exhausts through a diffuser with a second minimum to the atmosphere or into a pair of vacuum spheres, 41 and 60 feet in diameter. This tunnel produces speeds between Mach 7.5 and 8.0, depending on pressure. The maximum run time to vacuum is about 90 seconds, but runs as long as 10 minutes are possible when exhausting to the atmosphere. This tunnel has largely been on standby since the late 1970s, but it remains intact.[227]

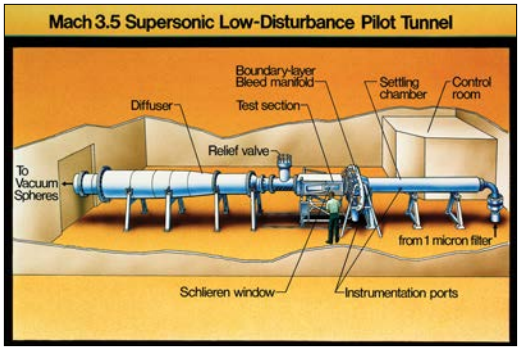
D116: 20-Inch Mach 8.5 Tunnel

Opened in 1961, the 20-Inch Mach 8.5 Tunnel was a conventional tunnel that generated the highest speed using air of all Langley tunnels. It used dry air heated by an electric resistance heater to 1,000°F. The settling chamber contained screens to stabilize the flow, which then passed through the axisymmetric nozzle and 21-inch-diameter test section. (Why "20-Inch" was chosen for its name is unknown.) The core test area measured 16 inches in diameter. A model injection system raised the model into the stabilized airstream. The sting had adjustments for pitch and yaw. The tunnel exhausted through a diffuser with a movable second minimum to the atmosphere or a vacuum sphere. The maximum run time to atmosphere was about 7 minutes and about 30 seconds to vacuum. This tunnel was demolished about 1980 to provide space for the Pilot Supersonic Low Disturbance Tunnel.[228]

D116: 6- by 10-Inch Supersonic Low-Disturbance Tunnel

The 6- by 10-Inch Supersonic Low-Disturbance Tunnel in Room D116 in 2000. Note the ring-shaped manifold and radial connections for the boundary-layer bleed system at the test section. (Photo credit: NASA LRC-2000-B701_P-00531)

Originally built in 1988 as the Pilot Supersonic Low Disturbance Tunnel, this facility is a Mach 3.5 conventional tunnel with specific features intended to produce a low-turbulence, or "quiet," flow through the core of its test section. Using air as the test gas, its quiet flow is achieved using a combination of settling chamber devices; a boundary-layer extraction system; and a highly polished, two-dimensional nozzle with a boundary-layer bleed upstream of its throat. Although a boundary does form in the nozzle that ultimately generates a shock wave and downstream turbulence, the design produces a very quiet core in the shape of a rhombus 5–10 inches by 1.5–3.6 inches in size (the size varies with Reynolds number). Since this tunnel exhausts to the atmosphere, typical run times range from 15 to 30 minutes. This tunnel's primary use has been in developing supersonic quiet-flow technology and computational methods.[229] The tunnel, now just referred to as the Supersonic Low Disturbance Tunnel, remains active.



This drawing identifies the major components of the 6- by 10-Inch Supersonic Low-Disturbance Tunnel. The boundary-layer bleed system extracts turbulent air next to the walls to produce more-uniform flow through the test section. (Image credit: NASA LRC-1993-B701_P-01742)

D118: Probe-Calibration Tunnel

The Probe-Calibration Tunnel in Room D118 in 1998. (Photo credit: NASA LRC-1998-B701_P-02323)

The Probe Calibration Tunnel is a conventional, open-jet pressure tunnel with three interchangeable nozzles, and it has adjustments for the independent control of pressure, temperature, and speed. Test section pressure can be varied from 0.13 to 10 atmospheres (2–146 psia), and stagnation temperature can be set from 0 to 200°F. Its three interchangeable nozzles provide a speed range of Mach 0.05–3.5. As its name indicates, this tunnel is used primarily to calibrate instrumentation used in the Hypersonic Facilities Complex's other tunnels. This tunnel is in service.[230]

Another tunnel, the 20-Inch Mach 6 CF_4 Tunnel, is operated as part of the Hypersonic Facilities Complex, although it is located in Building 1275, some distance from Building 1247. This tunnel is discussed in its own section.

4- BY 4-FOOT UNITARY PLAN WIND TUNNEL

Aerial view of Langley's Unitary Wind Tunnel building in 1972. (Photo credit: NASA LRC-1972-B701_P-00607)

SIGNIFICANCE

The 4- by 4-Foot Unitary Plan Wind Tunnel (UPWT) was one of a group of large, high-performance wind tunnels built under a joint, or "unitary," appropriation by Congress to provide supersonic wind tunnels for both military and civilian research and development. A new supersonic tunnel was built at each NACA laboratory and at a new Air Force development center.

Langley's UPWT was originally intended primarily for missile research, and it has the highest speed range of the NACA/NASA Unitary Plan tunnels. It includes two test sections with closed circuits driven by a common group of compressors, and it can generate continuously variable test speeds between Mach 1.5 and 4.6. This tunnel has tested almost all American missiles, supersonic aircraft, and spacecraft built since 1955.

DESCRIPTION

The UPWT occupies most of Building 1251 in Langley's West Area. Unlike most modern wind tunnels, which have much of their circuits exposed, the UPWT is completely enclosed within the building. It is a dual-circuit, supersonic tunnel with two test sections, one designed for a Mach range of 1.5–2.9, and the second for Mach 2.3–4.6. Both test sections measure 4 feet square by 7 feet long. The tunnel is constructed of steel plate and designed to operate over a pressure range of 0.1–10 atmospheres (2–147 psia). While the nozzles and test sections are rectangular, most of the ducts have circular cross sections. The overall dimensions of the tunnel approximate a rectangle measuring 210 by 263 feet.[231]

Each test section is at the end of an asymmetric nozzle equipped with a contoured sliding block for its floor and a fixed ceiling with a different contour. The two nozzles

function the same way, but their proportions are different to suit their different speed ranges. An electric motor, acting through a gearbox, turns lag screws to move the sliding block longitudinally. As it advances, the nozzle's throat area decreases while the length of its expansion section increases, thus raising the Mach number it generates. The nozzle can be adjusted during operation to produce any Mach number within its range. Each nozzle is preceded by a settling chamber approximately 25 feet long. Downstream from each test section is a variable-second-minimum section, with hinged sidewalls to stabilize the normal shock, and a diffuser.

Each test section incorporates multi-panel, optically clear windows on both sides for schlieren and shadowgraph photography and a sting mounted on a horizontal support bar. To support testing of missiles that can make extreme maneuvers, the sting can change the angle of attack from –15 to 30 degrees, traverse 40 inches across the test section's width, and move 36 inches longitudinally. Adapters are available to allow 310 degrees of roll and ±8 degrees of yaw adjustment. Most models have internal strain-gage balances, but an external balance is available for models that cannot have internal balances. Sidewall mountings are also possible for half models. In addition to the six-component balance arrangements, pressure-distribution and heat-transfer measurements can be made, and several flow-visualization techniques can be employed. The UPWT's data acquisition and control systems have been upgraded several times to enhance its capabilities.[232]

The most complex portion of the UPWT is its drive and compressor array, which has to generate pressure ratios between about 1.5 and 18 to 1, depending on the circuit in use; its nozzle setting; and the test's pressure requirements. Six centrifugal compressors, identified as "C" through "G" and "I," are connected in five different configurations to accomplish this. Compressors C, D, and I are primary compressors operating in parallel, and they are sufficient for speeds of up to Mach 2.2 in Test Section 1. For higher speeds requiring higher compression ratios, the output of these primary compressors goes in series through compressors E; E and F; or E, F, and G before being routed to either test section. Thirteen valves in the ducts isolate compressors and the test section not in use for any particular run. Compressor G is a 3-stage Clark Brothers machine, and the others are single-stage units manufactured by the Roots-Connersville Blower Corporation. Since they are on a common shaft, all six compressors turn in every configuration, but closed inlet valves prevent airflow and minimize energy losses in disconnected compressors. A 1981 modification reduces the air pressure around disconnected compressors to further reduce energy losses.[233]

The six compressors are driven by a 63,333-horsepower synchronous electric motor operating at 3,600 revolutions per minute. A 20,000-horsepower wound-rotor motor acting through a speed-increasing gearbox serves as a starting motor to bring the assembly up to operating speed, but this motor adds power during operation as well. Together these motors have a maximum rating of 100,000 horsepower for up to 30 minutes. The complete compressor-motor set is 120 feet long.[234]

Six water-cooled heat exchangers remove the heat of compression from the airstream. One is in the return duct, and the other five are immediately downstream of the compressors. Compressors C and D are served by a common exchanger, but the other compressors have individual units. Water circulated through these exchangers is pumped to a large cooling tower near the northwest side of the building. This cooling system can maintain approximately 100°F in the tunnel, but the heat exchangers can be bypassed for tests requiring hotter air.[235]

Pumps to evacuate or pressurize the tunnel and equipment to dry the makeup air are located in the building's northwest corner. A 3,500-horsepower compressor and desiccant dryer can produce 12,500 cubic feet per minute of air with a dew point of –90°F. It is stored at 150 psi in three outside spheres.[236]

HISTORY

After the end of World War II, the American aeronautics community, including researchers, manufacturers, and the armed services, realized that the new technologies of jet propulsion, swept wings, and rocket-powered missiles were opening the door to unprecedented advances in aircraft performance. As early as April 1945, researchers at NACA laboratories had begun recommending that the agency build new supersonic tunnels to enable the needed research. The concurrent rise of the Cold War made it imperative for the United States to invest in first-class research facilities that would enable it to master supersonic flight, particularly after the rocket-powered XS-1 proved that such flight was not only theoretically possible, but actually achievable under a pilot's control. A joint NACA-Air Force project, the XS-1's pioneering flight on 14 October 1947 came less than a month after the U.S. Air Force was created as a separate service, and powerful generals of the new service pressed hard for any development that would advance its capabilities and influence. Not wanting to be outdone, the Navy's Bureau of Aeronautics also established a joint project with the NACA that produced the D-558-1, a jet-powered research plane capable of Mach 0.99.

In-flight data from these research airplanes showed some significant discrepancies from wind-tunnel tests run during their design, most seriously in the transonic and supersonic speed ranges. These data reinforced the belief of many researchers that new, advanced wind tunnels were essential if these flight regimes were to be exploited. Engineers in the NACA, Navy, and Air Force had confidence that large supersonic tunnels[237] could be built, and each organization developed plans for a new supersonic research center, though they were well aware that the cost and power requirements would be enormous. Ultimately realizing that Congress would not fund separate massive construction projects for each, the NACA and the armed services took the unprecedented step of proposing "...a unitary program to provide for the coordinated responsibilities of the Army [*sic*], Navy, CAA, and NACA...."[238]

After considerable debate and revision, Congress passed the National Unitary Wind Tunnel Act of 1949, authorizing $136 million for three NACA tunnels, one at each of

its laboratories. The act also authorized $100 million for the Air Force to build a new development center at Tullahoma, Tennessee, and $10 million for certain university tunnels. The NACA's funding was for an engine research tunnel at the Lewis Laboratory in Cleveland, Ohio; an aeronautical tunnel at the Ames Laboratory in Moffett Field, California; and the highest-speed tunnel for missile research at Langley.[239]

Design and construction of Langley's UPWT began immediately. Each of the Unitary Plan tunnels had novel features, but Langley's UPWT was, by far, the most unusual design. This stemmed primarily from its missile-development role that demanded the highest speed range and greatest range of operating pressures of the group. Meeting these requirements resulted in a very complex wind tunnel.

Researchers at Ames had developed a variable nozzle for its 6-Foot Supersonic Tunnel that changed speed by sliding horizontally to alter the size of the nozzle's throat, and this asymmetric nozzle worked well. But a single nozzle could not be proportioned to provide the entire speed range desired, Mach 1.5–4.6, so the UPWT was designed with two separate circuits, one designed for Mach 1.5–2.9, and the second for Mach 2.3–4.6. A common set of compressors would serve both circuits, but only one circuit could run at a time.[240]

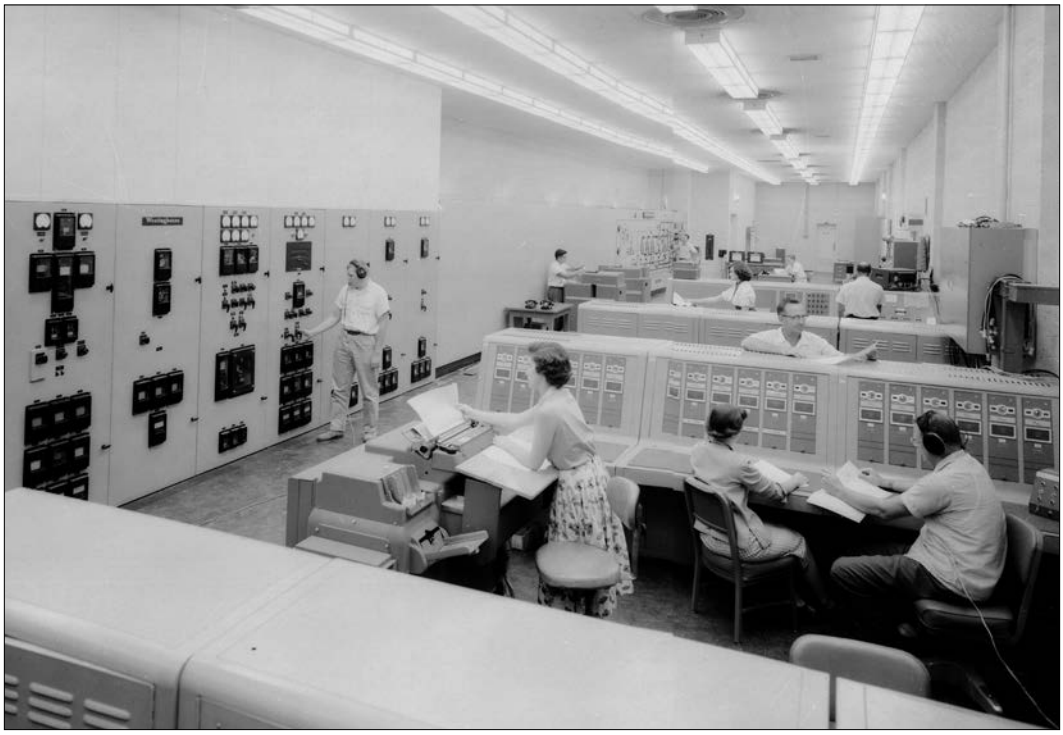
The continuously variable Mach number range and dual circuits demanded a wide range of compression ratio and airflow. The nozzle setting would determine the expansion ratio and test speed, but the compressor system had to be able to match that with the correct pressure ratio and flow volume. This resulted in the most complex compressor and drive system ever installed in a wind tunnel. The design team, led by Herbert A. Wilson, devised a system that utilized six centrifugal compressors, driven by one or two electric motors, and a set of supply and bypass ducts with valves to configure the system in five different modes to generate the proper airflow and pressure for each run. The design team specified six water-cooled heat exchangers in the various ducts to remove the heat of compression, which was transferred to the atmosphere through a large, 16-cell cooling tower.[241]

Following a construction period of about three years, the complicated UPWT first ran in 1955. Calibration tests revealed that the complicated design worked as intended, producing consistent, stable flows in both test sections. The UPWT had cost more than $15.4 million to build, but bookings for test programs soon filled its schedule and began to justify the investment. As anticipated, many of the early test programs involved missiles or missile components, but most American supersonic aircraft, including NASA's Supersonic Commercial Air Transport (SCAT) design, found their way into the schedule as well. By the 1980s, a significant portion of the test programs involved basic research, including heat-transfer and boundary-layer-separation studies. This is still the case, but airplane and spacecraft programs continue to use the tunnel.[242]

The UPWT has been improved through several modification programs since 1955. Most of these have involved computerized controls and advanced instrumentation and flow-visualization capabilities. Current flow-visualization techniques include schlieren

photography, vapor screens, sublimation, laser doppler velocimetry, and conventional surface techniques such as tufts and oil-flow. The UPWT's basic mechanical design has remained intact and reliable, though Langley has done studies to see if efficiency improvements were possible. One such study in 1981 recommended reducing the pressure in bypass ducts to reduce the power consumption of compressors in certain situations, a modification that was quickly done.[243]

Langley's UPWT remains in service as one of the center's most productive tunnels. It has contributed to NASA programs such as the Crew Exploration Vehicle, Crew Launch Vehicle, Hyper-X (X-43), and X-43C. Its speed range, flexibility, and reliability continue to make it attractive to a variety of government and industry users.



The Unitary Plan Wind Tunnel's control room was one of the largest and most complex built up to that time. In the 1956 view, the drive controls are on the left wall, and data recording equipment cabinets occupy the foreground. The air system controls are barely visible in the background. Modern computers now dominate the data acquisition area. (Photo credit: NASA LRC-1956-B701_P-95481)

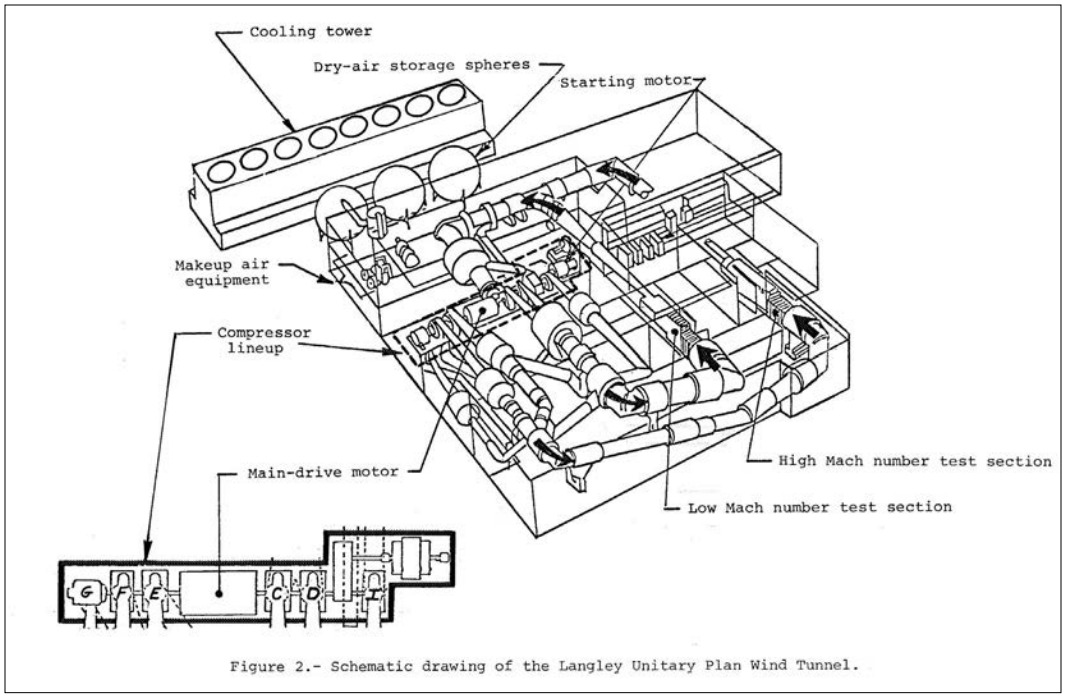
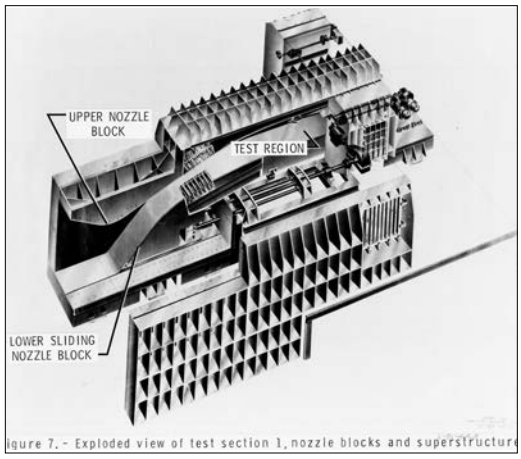
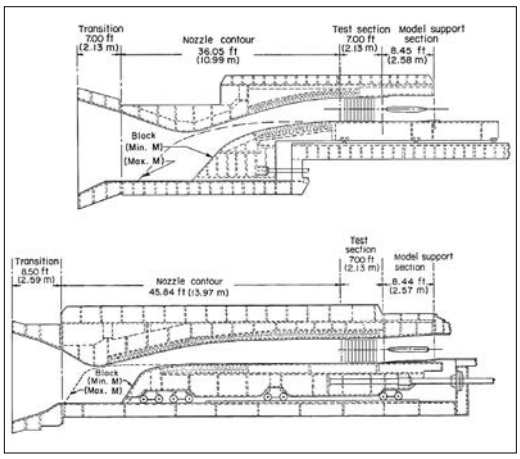


Figure 2.- Schematic drawing of the Langley Unitary Plan Wind Tunnel.

This drawing of the Unitary Plan Wind Tunnel clearly shows its complexity. Note how the six compressors deliver air to either of the two test sections through a network of interconnected ducts. Each duct contains a heat exchanger to remove compression heat from the air. Valves in the ducts isolate portions not in use for any particular test. (Image credit: NASA TP-1905, Fig. 2)

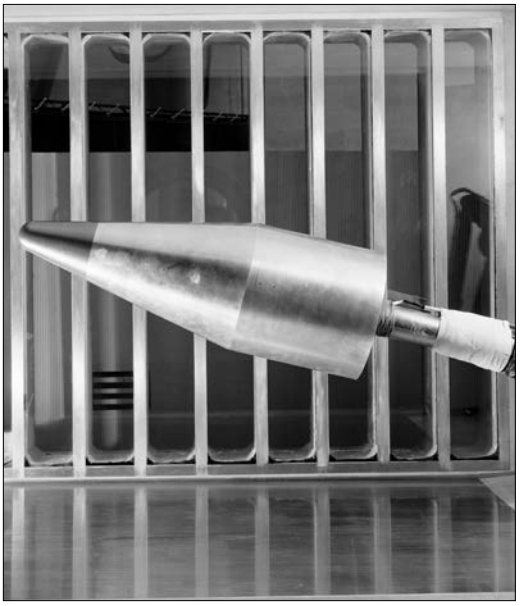


igure 7.- Exploded view of test section 1, nozzle blocks and superstructure

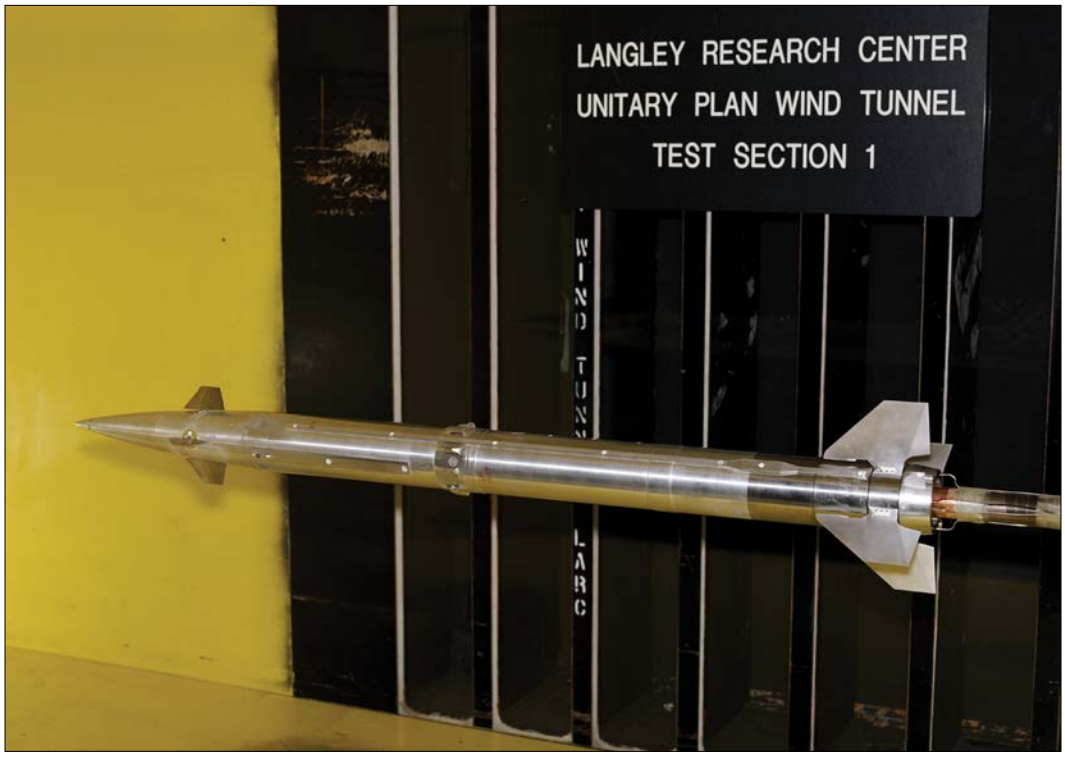


Each of the Unitary Plan Wind Tunnel's test sections uses an asymmetric, sliding-block nozzle. The pictorial drawing (left) shows the low-speed nozzle with one wall moved out. The two nozzles are similar, but proportioned differently, as the section drawing (right), drawn to the same scale, illustrates. The low-speed nozzle is the shorter of the two. Air flow is from left to right. Electric motors turn lag screws to position the sliding blocks. (Image credits: NASA LRC-1981-B701_P-00228 and NASA TP-1905, Fig. 12)

This 1980 image shows the bank of six centrifugal compressors, with the main drive motor in the center, that powers the Unitary Plan Wind Tunnel. A second motor, not visible, assists with starting and in high-power situations. The maximum available power is 100,000 horsepower. (Photo credit: LRC-1980-B701_P-02309)

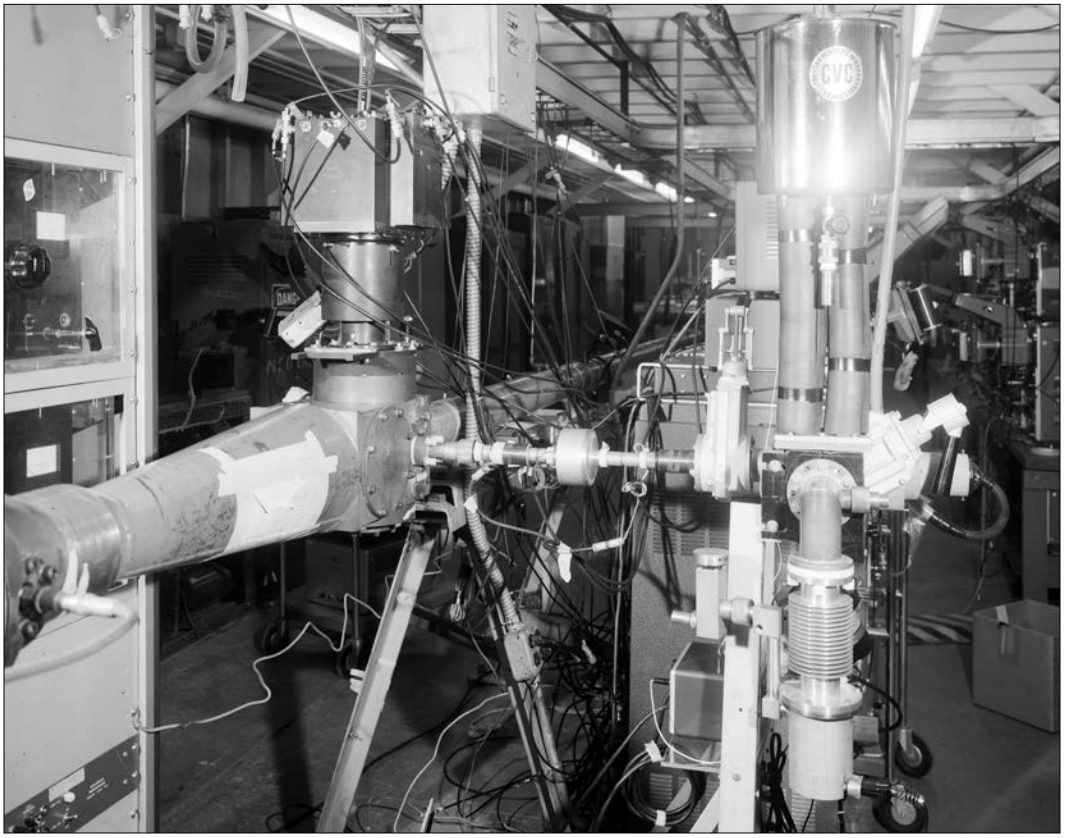


These photos show two of the many missile and component tests in the Unitary Plan Wind Tunnel during the late 1950s. Left view is of a Jupiter nose cone during a 1957 test, and right view shows a Mercury-Redstone spacecraft-booster stack tested in 1959. (Photo credits: NASA LRC-1957-B701_P-00700 and NASA LRC-1959-B701_P-03983)



Unitary Plan Wind Tunnel test programs during the 2000s have included the SA-8 missile in low-speed test section 1 (top) and a Hyper-X scramjet plane in high-speed test section 2 (bottom). (Photo credits: NASA LRC-2000-B701-01514 and NASA LRC-2000-B701_P-00011)

PILOT MODEL EXPANSION TUBE



A view of the Pilot Model Expansion Tube in 1972. (Photo credit: NASA LRC-1972-B701_P-01176)

SIGNIFICANCE

The Pilot Model Expansion Tube (PMET) was NASA's prototype expansion tube type of impulse tunnel. It proved that the concept was valid and generated speeds higher than those produced in earlier types of impulse tunnels, and it served as a model for subsequent expansion tubes at Langley and elsewhere.

DESCRIPTION

The PMET appeared to be a pipe approximately 6 inches in diameter (3.75 inches inside diameter) and 71 feet long with a slightly larger cylinder surrounded by electrical cables on one end and a 3-foot-diameter cylinder with a conical connection to the pipe on the other. The larger cylinder, 20 feet long, contained what was known as the dump tank, whose forward portion contained the test section. The 81 coaxial cables connected electrodes in the tunnel's driver to a 12-kilovolt capacitor bank able to store 2.5 million joules of electrical energy. When released, this energy generated high-intensity arcs across the electrodes within the collector that were the tunnels' driving force. [244]

The tunnel was located in Building 1247-G in Langley's West Area, a structure northeast of the Hypersonic Facilities Complex. It was mounted approximately 5 feet above the concrete floor on structural-steel bents. The PMET's ancillary equipment, primarily vacuum pumps and the capacitor bank, were located in the same building close to the tunnel, except for helium and hydrogen bottles that were mounted just outside the structure.

To achieve its maximum speed of approximately Mach 30, the PMET needed a very high vacuum in its shock tube and test section/dump tank. A roughing pump extracted over 99 percent of the gas in the tunnel, and a diffusion pump removed most of what remained, producing a vacuum on the order of 0.007 psia. A separate vacuum pump evacuated the driver chamber before the helium or hydrogen driver gas was admitted. All joints in the PMET were fitted with seals capable of sealing against even the slightest leak.

Both helium and hydrogen were available as driver gases. The helium bottles stored that gas at 2,000 psi, but those used for hydrogen were rated for 5,000 psi. Air, initially charged into the intermediate chamber between the driver chamber and shock tube, was the usual test gas, but any gas or mixture could be used if desired.

A sting held models in the test section. Run times ranged from 50 to 400 microseconds; thus, the PMET required some of the fastest-response instrumentation available at the time.

HISTORY

By 1960, a number of impulse tunnels were in operation at NASA centers and elsewhere to produce very high speeds, albeit for very short times, typically about 100 milliseconds. They were, however, capable of generating speeds of up to approximately Mach 25, higher than other types of wind tunnels. In general, impulse tunnels work by having an instantaneous burst of energy heat a gas, which then flows through a nozzle and past a model to a vacuum chamber usually referred to as a dump tank. Diaphragms designed to rupture at specific pressures keep the gas, or gasses, and vacuum apart before the run, and they had to be replaced between runs.

Several types of impulse tunnels exist, differentiated by the way gasses are used, the type of initiation, and the number of internal chambers. The simplest is the hotshot tunnel. The test gas, usually nitrogen, is charged into a chamber that is separated from the evacuated nozzle, test section, and dump tank. The gas is rapidly heated, usually by an electric arc, to around 10,000°F, which generates pressures of up to 2,000 atmospheres. The gas ruptures the diaphragm and flows through the nozzle, past the model, and into the dump tank. A shock tube adds a second diaphragm to create two chambers ahead of the nozzle. The first chamber is charged with a light "driver" gas such as helium under pressure, while the second is filled with the test gas. The run is initiated by heating the driver gas. The rising pressure ruptures the first diaphragm, generating a shock that travels through the second chamber and reflects off the nozzle contraction. This compresses and heats the test gas, which then ruptures the second diaphragm and

passes through the nozzle and tube. The additional compression and heating allow the shock tube to produce speeds as much as twice those in a hotshot tunnel.[245]

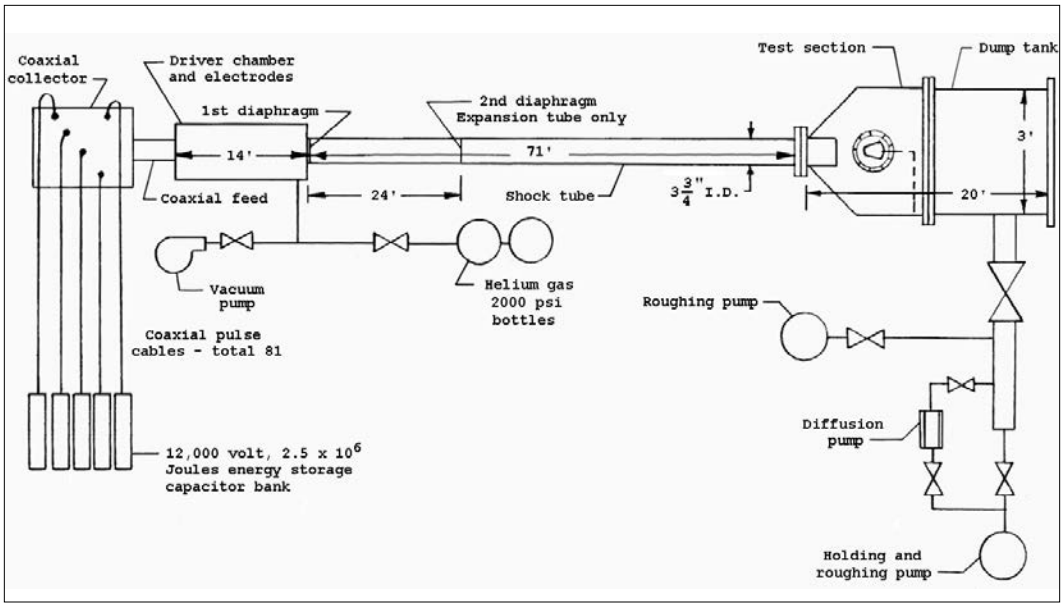
About 1961, Langley engineer Robert Trimpi, having considerable experience with hypersonic tunnels of all types, conceived of an improvement that could increase test speeds still farther. In simplest terms, he combined the dual-gas design of a shock tube with a long, third chamber that he termed an expansion tube. Its operation began like a shock tube, but the second diaphragm was designed to rupture at a relatively low pressure when struck by the shock wave rather than reflect it. The test gas, heated and accelerated by the shock wave, then expanded into the evacuated expansion tube, which accelerated it a second time, and the expansion cooled it as well. Thus, the flow impinging on the model was both very fast and very cold, closely resembling the conditions of a spacecraft reentering the upper atmosphere.[246]

As was commonly done with a new technology at Langley, Trimpi received authorization to build a pilot device. Combining some components from an existing combustion-driven shock tube with many new ones, he and his team built the Pilot Model Expansion Tube in Building 1247-G. The PMET worked as designed, generating test speeds of up to Mach 30 for between 50 and 400 microseconds. Eliminating the second diaphragm transformed the PMET into a shock tube capable of Mach 3 flow for between 200 and 500 microseconds, giving it additional versatility.[247]

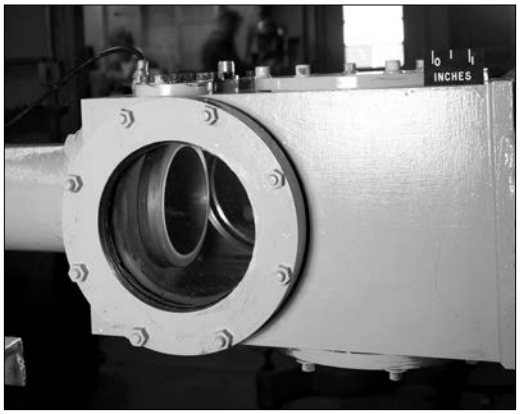
As with all impulse tunnels, technicians had to replace the diaphragms with new ones for each run. The first, high-pressure diaphragm was a metal disk approximately 1/16-inch thick with an "X" machined into one side. This groove determined the burst strength and assured that the disk would rupture in a pre-determined fashion to help ensure stable flow. The second, low-pressure diaphragm could be thin metal, plastic, or even wax paper.

Researchers used the PMET to validate Trimpi's theory and answer a number of practical questions about the operation of the actual device, including questions about boundary-layer growth, shock wave attenuation, effects of driver and test gas mixing, and run times. They evaluated different driver and test gases as well as different diaphragm materials. This work successfully validated the theory and demonstrated that the expansion tube was a viable research tool for very high Mach number flow.[248]

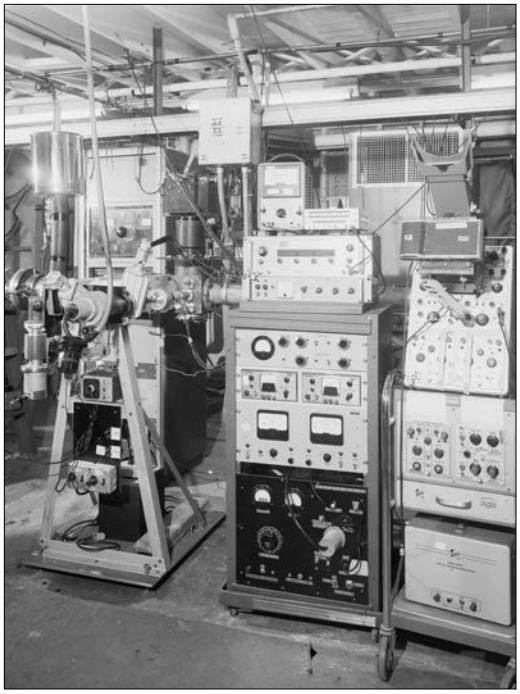
Having fulfilled its main purpose of proving the expansion-tube concept, the PMET justified construction of the larger 6-Inch Expansion Tube, including Building 1200 to house it. But it remained in place for several years after the 6-Inch Expansion Tube's completion in 1966, used for a variety of pilot studies. Interest in hypersonic research waned in the 1980s, and NASA demolished several of its hypersonic facilities. While no records of its disposal have been located, the PMET was likely demolished about this time. No portion of it is known to survive.



This diagram, although not to scale, shows the major components and dimensions of the Pilot Model Expansion Tube. The second diaphragm and the 24-foot-long section ahead of it are the major differences between expansion and shock tubes. Omitting the second diaphragm allowed the PMET to function as a shock tube. (Image credit: NASA TM X-1130-PMET)



This view shows the Pilot Model Expansion Tube's test section in 1965. Note the scale at upper right for a sense of size. (Photo credit: NASA LRC-1965-B701_P-02186)



Experimental apparatus installed in the Pilot Model Expansion Tube in 1972. (Photo credit: NASA LRC-1972-B701_P-01175)

9- BY 6-FOOT THERMAL STRUCTURES TUNNEL

This 1969 view of the 9- by 6-Foot Thermal Structures Tunnel shows its air storage bottle field behind, the heat exchanger and test section portions of the tunnel in the middle, and the exhaust diffuser at right. (Photo credit: LRC-1969-B701_P-03130)

SIGNIFICANCE

The 9-by 6-Foot Thermal Structures Tunnel (TST)[249] was the NACA's first large supersonic tunnel capable of producing Mach 3 flows at temperatures of up to 660°F. The tunnel performed critical testing of high-temperature materials for America's early supersonic aircraft, missiles, and, later, both crewed and uncrewed spacecraft.

DESCRIPTION

The TST occupied Building 1256 in Langley's West Area. It was an intermittent blowdown tunnel that exhausted horizontally to the atmosphere. Dominating its exterior were 12 vertical air-storage bottles arranged in pairs with pipe connections at their hemispherical tops and manifold connections at their base. Altogether, the bottles held 130,000 cubic feet of air at 600 psi. The compressed air was supplied from the base's central system.[250]

A masonry building housed the nozzle, test section, and supporting offices and shops. The nozzle was two-dimensional with contoured top and bottom walls designed for Mach 3. The test section measured 6 feet high; 8 feet, 9 inches wide; and 10 feet long. Models were supported on one or more stings mounted on a turntable that was flush with the floor. Temperature probes and quick-response pressure transducers were the most-commonly used instruments. After 1959, their data were recorded onto magnetic tape by a high-speed data-collection system, and an automatic sequencer controlled the test runs. The test section walls and ceiling had multiple windows for lighting,

observing, and filming tests from various angles. Initially, the test section exhaust exited to the atmosphere through a port in the north wall, but a diffuser intended to reduce the tunnel's noise was installed in 1960. It extended 97 feet north of the building.[251]

The area between the bottle field and the nozzle was occupied by a large horizontal cylinder that housed the combined heat exchanger and settling chamber, and by the main valves that controlled the air flow. The heat exchanger used a propane burner to pre-heat a metallic-mass core before each run. This arrangement could produce test section stagnation temperatures of up to 660°F. In 1963, another propane burner was added to supplement the heat exchanger during runs. It could heat the core flow to 2,000°F.[252]

HISTORY

The problem of aerodynamic heating and its effects on airplane and spacecraft materials and structures came to light—literally—with the German V-2 ballistic missile during World War II. Reentering the denser portion of the atmosphere at Mach 5, a few of these missiles were seen to glow a dull red as they descended on London during night-time attacks. It had long been known that most materials, especially metals, weaken at elevated temperatures, but this had not been an issue with subsonic airframes. The rapid advances in airplane and missile performance during the two decades following the war made an understanding of aerothermodynamics and high-temperature structural mechanics essential for aerospace engineers.

Materials researchers at Langley had begun experimenting with various methods to simulate aerodynamic heating in the early 1950s, using such things as carbon-rod radiators, ceramic heaters, and quartz lamps. While these could produce the heat desired, they had no airflow and, thus, could not produce the aerodynamic forces that can reshape softened or melted objects.

Another technique used arc jets, which could produce high-temperature airflows, but these devices had limitations, too. They operated by passing compressed air through a settling chamber lined with copper electrodes. Massive amounts of electricity generated arcs between the electrodes that heated the air to temperatures between about 1,600 and 14,500°F before it passed through a nozzle and impacted the test subject. Test speeds ranged from approximately Mach 0.1 to 7, but the largest test section measured only 6.3 inches in diameter, and there was concern over contamination from the electrodes. Arc jets of the time were useful for materials-development work, but they lacked the capability to test full-size panels in conditions that closely simulated both the aerodynamic and thermodynamic parameters of supersonic or hypersonic flight.[253]

Following the recommendations of an advisory committee in 1951, the NACA approved the construction of a high-temperature structures laboratory at Langley, even though no specific design for one had been proposed. Some believed a heated test chamber would be adequate, but continued study and experience indicated that such a chamber would not reasonably reproduce the in-flight conditions at high-supersonic speeds and above. By 1953, it was evident that any new facility would need to generate

flows that combined high speed and high temperature in a test section large enough to test models up to at least 2 feet in diameter.

The facility that emerged from the design team, led by Richard R. Heldenfels and E. Barton Geer, became the TST, the NACA's first large facility able to generate the high speeds and temperatures needed for this kind of materials research. Following a common practice at Langley, Heldenfels and Geer built a 1/12 -scale pilot model to refine their design. This 9- by 6-inch pilot tunnel proved the concept, and it remained in service performing preliminary tests to minimize model blockage problems after completion of the full-sized tunnel. Construction was authorized in 1953, but it proceeded slower than anticipated. A federal budget reduction and some technical problems combined to delay completion by several months, but the TST finally opened in September 1957.[254]

Researchers used the TST to test a wide variety of structural materials and components, with many programs involving panel flutter. The mechanical properties of the aluminum alloys commonly used in aircraft construction begin to change significantly at temperatures as low as 300°F. These changes reduce aluminum's strength and stiffness, which in turn increase its susceptibility to buckling and flutter, both of which can be fatal problems for airplanes and missiles above about Mach 2. Being able to produce stagnation temperatures between 200 and 660°F at Mach 3 made the TST ideal for this work, although test times were limited to a maximum of 55 seconds. Some of the test programs involved specific aircraft, while others investigated general properties and behavior, including localized aerodynamic heat transfer, boundary-layer transition, and thermal stress.[255]

The TST was not without its problems, however. When the tunnel started, the flow separated from the nozzle walls and a shock wave raced through the test section. A similar disruption occurred during shutdowns. Though short-lived, the turbulence and shock were strong enough to damage models. Researchers first tried movable shields to protect the models during these transient events, but they ultimately developed a model-injection device that inserted the model into the airstream after it stabilized at Mach 3 and removed it before shutdown. A door protected the model when retracted.[256]

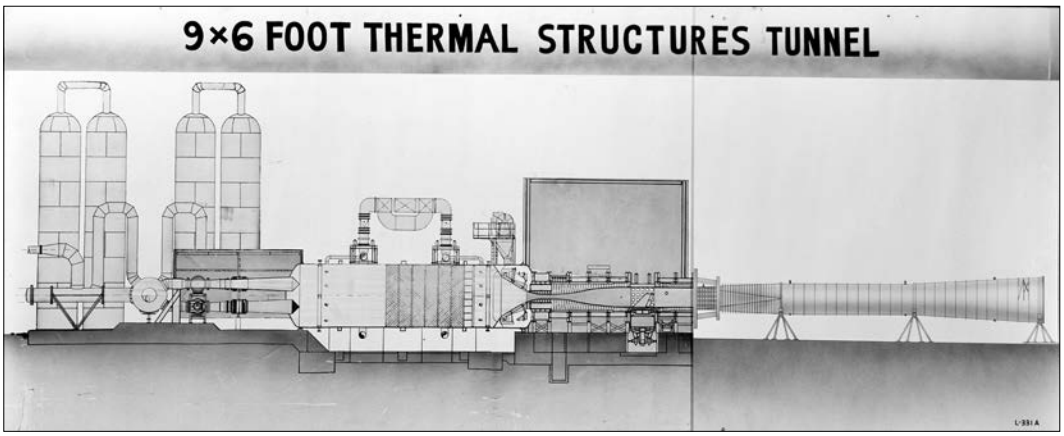
As interest in space exploration grew, the TST staff upgraded the facility with several modifications to better simulate atmospheric reentry conditions. These included a topping compressor to boost the air pressure in 1961 and a propane burner in the settling chamber to generate core temperatures in the test section as high as 2,000°F in 1963. With these modifications, the TST hosted tests of numerous missile components as well as Gemini and Apollo heat shields.[257]

When the TST entered service, it immediately gained the distinction of being by far Langley's loudest facility. Its designers had calculated that its exhaust jet would be the equivalent of a rocket producing 475,000 pounds of thrust—approximately 30 percent more than an Atlas, America's largest rocket at the time—so they expected a lot of noise, and they were not disappointed! An acoustic survey measured sound pressures as high as 142 decibels 450 feet from the exhaust, and around 100 decibels between 2,000 and

6,000 feet away. Sound this loud is not simply annoying, but physically detrimental to humans. The TST had been located so that its exhaust was directed northward over a large marshy area to minimize its effect on both the laboratory and Langley Air Force Base, but the roar was clearly audible in Poquoson, a town about 5 miles north. Engineers added a 97-foot-long diffuser to the exhaust to slow the exhaust speed and attenuate some of the noise. Tests revealed that the sound levels were similar to those measured without the diffuser but shifted about two octaves lower in frequency. Even with the diffuser, TST operators employed a 5-minute warning sequence to alert people in the area that a run was imminent.[258]

Those conducting the acoustic survey realized the high noise level could be useful. During launch, an astronaut in a Mercury capsule would be subjected to a sound environment very similar to the one near the TST's exhaust, so the location seemed ideal for evaluating the sound profile inside the spacecraft. In what may be the most unusual application of a wind tunnel, both uncrewed and crewed tests confirmed that the interior noise level was satisfactory.[259]

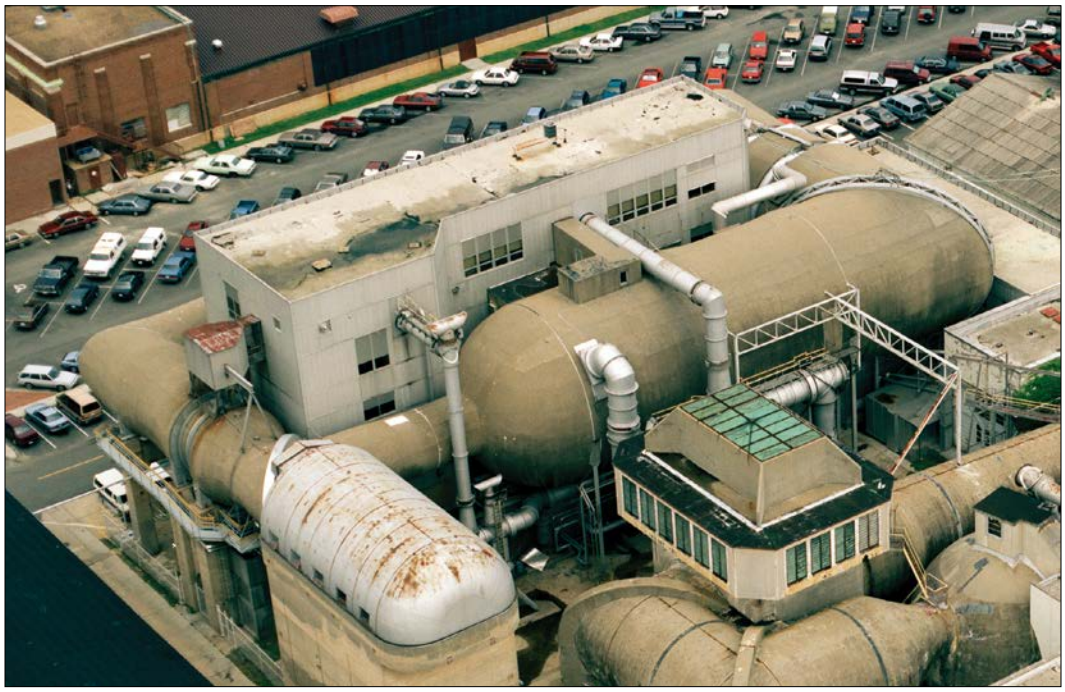
The TST remained in reliable service until 30 September 1971, when its service life ended in an appropriately loud manner. Fatigue from thousands of pressurization cycles had weakened a fitting at the top of one of the 600-psi air storage bottles, causing a minute crack to grow until it reached the point where the part suddenly failed catastrophically. Debris roared skyward and damaged several parked cars, but fortunately no one was injured. Langley deemed it too expensive to rebuild or replace the air system and closed the tunnel. All of the TST components were removed about 1975, and the building was converted for other uses. Building 1256 now houses the Combined Loads Test System Facility, but nothing remains of the TST.[260]



The major components of the 9- by 6-Foot Thermal Structures Tunnel are labeled on this 1960 drawing. The 97-foot-long diffuser was added in 1960 to reduce noise, but even with the diffuser, the tunnel remained loud throughout its life. (Image credit: LRC-1960-B701_P-07256)

Technicians installing a model of an Apollo Command Module in the 9- by 6-Foot Thermal Structures Tunnel in 1962 for tests of possible heat-shield materials. This test program, which also involved rocket flights and other wind tunnels, was known as Project Fire. Note the floor turntable, the multiple circular viewing windows, and the marshland visible through the exhaust opening. (Photo credit: LRC-1962-B701_P-08895)

8-FOOT TRANSONIC PRESSURE TUNNEL



The 8-Foot Transonic Pressure Tunnel, seen here in 1992, was Langley's first wind tunnel designed and built from scratch as a transonic tunnel. (Photo credit: NASA LRC-1992-B701_P-08849)

SIGNIFICANCE

The 8-Foot Transonic Pressure Tunnel (TPT) was the NACA's first wind tunnel initially designed and built with slotted walls for transonic research and its first transonic tunnel to be pressurized for testing at higher Reynolds numbers. This tunnel was the site of significant transonic and boundary-layer-control research for four decades.

DESCRIPTION

The TPT is a closed-circuit, single-return, steel-shell wind tunnel mounted on structural steel bents. With a centerline approximately 20 feet above grade, it has mitered corners with turning vanes and a 36-foot-diameter enclosure around the test section that serves as the pressure shell in that region as well as the plenum for the test section slots. The test section measures 85.5 inches square and has 8.55-inch-radius fillets at all four corners. This gives it a cross-sectional area equal to an 8-foot-diameter circle. Both side walls have multiple observation and schlieren windows. The top and bottom walls have contoured slots that allow a continuous variation in Mach number from 0.2 to 1.2. The slot contours were based on experience in the 8-Foot transonic Tunnel, supplemented by experimentation in the TPT. They have adjustable reentry flaps and can be covered for totally subsonic testing. Most models are mounted on a sting that is

supported by a circular-arc strut that allows angle-of-attack adjustment, but sidewall mounting is also possible.[261]

The TPT includes a complex air system that controls the tunnel pressure between 0.25 and 2 atmospheres (3.7–29.4 psia) and provides substantial boundary-layer suction that allows larger models to be tested at Mach 1.15 to 1.3. This system, which includes two Elliot compressors rated for 96,000 cubic feet of air per minute each at a 4:1 compression ratio, precoolers, aftercoolers, and a dryer, removes air from the plenum and returns it to the circuit through trailing-edge slots in the turning vanes of turn 1. Each of the three-stage, centrifugal compressors is driven by a 4,000-horsepower electric motor. The air system equipment is located on the high-bay ground floor and mezzanine of the tunnel's equipment building, a three-story steel-frame-and-siding structure that also houses the tunnel's control room on the second floor and the 2-Foot Hypersonic Tunnel on the third.[262]

The TPT is powered by a 25,000-horsepower, variable-speed electric motor mounted on a large concrete pedestal at the tunnel's southwest corner. The motor is enclosed in a semicylindrical housing. It turns a multiblade fan whose blades extend from a streamlined nacelle. One inlet and two outlet rings of stationary blades stabilize the flow and minimize swirl.[263]

Cooling coils just ahead of the fourth turn provide some degree of temperature control. Water circulated through them passes through a cooling tower where the heat from the tunnel is exchanged to the atmosphere. The tunnel's exterior is also coated with a layer of blown concrete insulation for sound absorption, and it is painted white to minimize solar heat gain. At speeds above approximately Mach 0.6, the air temperature inside the tunnel typically ranges between 100 and 120°F, depending on the season.[264]

The TPT's control room is located on the second floor of the equipment building, and it has direct access to the plenum and test section through an airlock. The primary controls for tunnel operation were originally mounted in a panel that faced windows into the plenum and test section. Cabinets for instrumentation and data acquisition were placed adjacent to it as needed. A computerized console replaced the original one during the 1980s. Controls for the air system occupied a large panel with a graphic representation of the tunnel along the north wall, opposite the operating console.

A renewed interest in laminar flow control (LFC) over supercritical wings initiated a major modification to the TPT in 1981. The needed changes involved three areas: a contoured liner for the test section, a boundary-layer-removal system for the test wing, and flow-straightening devices in the settling chamber. The LFC test model was a vertically mounted swept wing with internal ducts for air extraction through slots of holes in the wing's skin. A 10,000-cubic-foot-per-minute air compressor with a 4.5:1 compression ratio furnished suction for the wing and returned the air to the tunnel. The test section liner did not have slots, but it was contoured to follow the calculated streamlines at Mach 0.82. To ensure smooth flow into the test section, engineers added a honeycomb and five 30-mesh screens immediately ahead of the contraction. The

LFC liner was removed at the completion of this program in 1988, but the other LFC components remained in place.[265]

HISTORY

The TPT grew out of Langley's experience with the slotted test sections installed in the 8- and 16-Foot Transonic Tunnels. Slot design was an ongoing effort well into the 1950s, but other problems arose that additional modifications could not easily cure. The primary ones were high levels of turbulence, high humidity, and low Reynolds numbers. The worst of these was humidity. Both transonic tunnels used air exchange for temperature control. Compression heat was substantial near Mach 1, so cooling was essential. During humid summer months, the incoming air contained sufficient moisture that the reduction of pressure in the test section would cause it to condense and form fog. Not only did this make observation difficult, but it altered the test conditions and damaged instruments. The cure was to replace the air-exchange tower with cooling coils that would not introduce outside air. While the contraction ratios of the 8- and 16-foot tunnels had been adequate for their initial speeds, they were insufficient for the transonic range. As the LTPT had shown, a higher contraction ratio would help considerably. The need for higher Reynolds numbers could be best satisfied by pressurization, something not possible in the existing transonic tunnels.[266]

Since it was impractical to solve these problems in the existing tunnels, John Stack and other engineers in his division, including Eugene C. Draley, Ray H. Wright, and Axel T. Mattson, began working on a design for a new tunnel that included the needed features in 1950. The transonic pressure tunnel they designed would be closed to the outside and use cooling coils for heat removal, pressurized up to 2 atmospheres to increase Reynolds numbers, and feature a 20:1 contraction ratio to minimize turbulence. The new tunnel would have a slotted test section, but with slots more carefully contoured to better suit a range of Mach numbers, and a 25,000-horsepower drive to generate speeds of up to Mach 1.3. A large boundary-layer-removal system would allow large models to be tested without significant blockage effects at Mach 1 and above. Sophisticated controls would allow operators to vary these parameters independently.[267]

The NACA authorized the new tunnel in 1950, and construction began immediately. Instead of building it in the West Area, the committee and Langley engineers decided to demolish the Propeller Research Tunnel in the East Area and erect the TPT in that space. Construction proceeded at a rapid pace, and the TPT opened in mid-1953. Its combination of features proved to be very successful, and the TPT was quickly booked for a wide variety of transonic test programs. Many of the new Navy and Air Force supersonic planes were evaluated for transonic performance, including control response and flutter, during the 1950s. During the next two decades, a long line of missiles, reentry vehicles, and spacecraft saw similar testing in the TPT.[268]

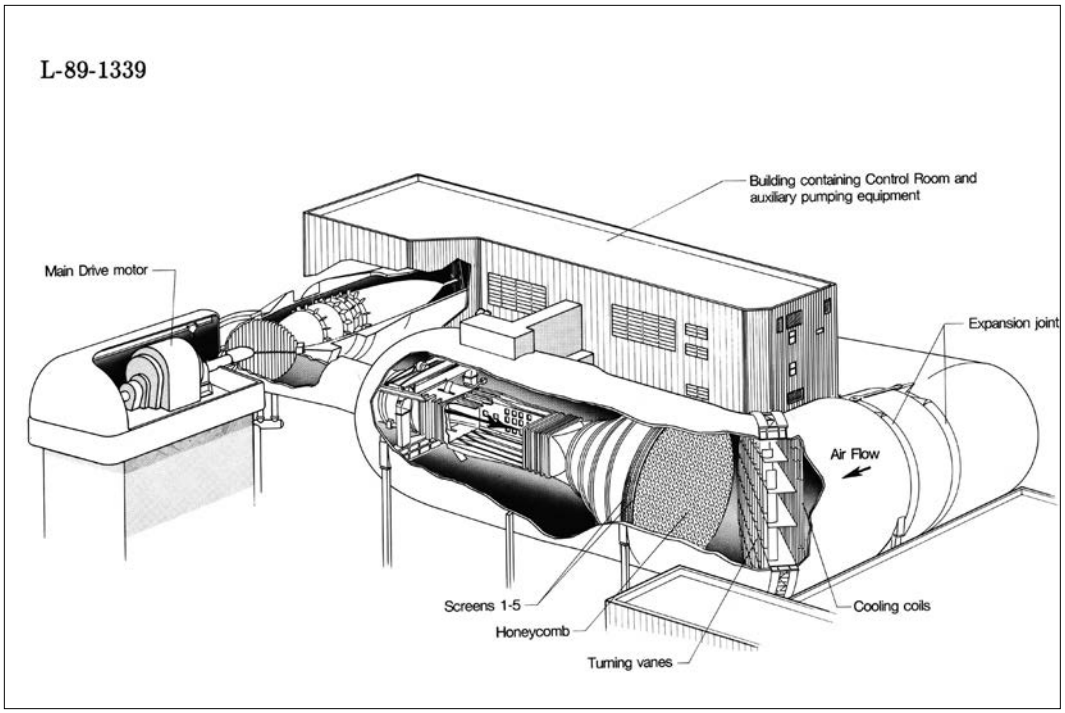
During the mid-1950s, external pipes were installed between the TPT's plenum and the test section and diffuser of the 8-Foot TT. This enabled use of the latter's drive as

a vacuum pump to assist the former's boundary-layer-removal system. Air extracted through the 8-Foot TT exhausted to atmosphere through its air exchange tower. Use of this system was discontinued when the 8-Foot TT closed in 1960, but the pipes remained in place with valves closed to seal it off from the TPT.

As noted above, the TPT underwent substantial modification in 1981 to support LFC research, which lasted through 1988 and demonstrated both the potential and frustrating practical limitations of boundary-layer-removal systems in airplane wings. In another attempt to develop a practical system, one manufacturer worked with Langley researchers to design a hybrid laminar flow control (HLFC) system during 1993–94. Its distinction was to utilize suction only near the wing's leading edge and rely on geometry to delay transition as far aft as possible. This particular project is significant for its extensive use of computational fluid dynamics (CFD) code in designing the airfoil and skin penetrations. The design was tested in the TPT during 1995, using a test section liner and airfoil mounting similar to that in the 1980s studies, but refined using CFD. Although these tests did not point to any specific design, they generated a massive amount of data that helped those writing CFD code to refine several aspects of their models.[269]

Budget pressures during and after the 1990s forced NASA to examine the economic viability of its facilities, and this resulted in the closing of numerous wind tunnels, including the TPT, which closed in 1996 and was demolished in 2011.

An experimental model installed in the Transonic Pressure Tunnel's test section in 1975. (Photo credit: NASA LRC-1975-B701_P-02471)



This cutaway drawing of the TPT identifies its major components. The boundary-layer compressors and other air system equipment (not shown) were located on the ground floor and mezzanine of the central building. (Image credit: NASA LRC-1989-B701_P-01339)

Technicians remove casing from one of the two compressors on the Transonic Pressure Tunnel's mezzanine that removed boundary-layer air from the tunnel. Each of these Elliot three-stage, centrifugal compressors had a 4:1 compression ratio and could move 96,000 cubic feet of air per minute. A 4,000-horsepower electric motor drove each compressor. A separate 10,000-cubic-feet-per-minute compressor (not visible) maintained pressure in the tunnel. (Photo credit: NASA LRC-1960-B701-P-04638)

The Transonic Pressure Tunnel's control equipment, seen here in 1973, changed over the years to keep the facility up to date. (Photo credit: NASA LRC-1973-B701_P-02594)

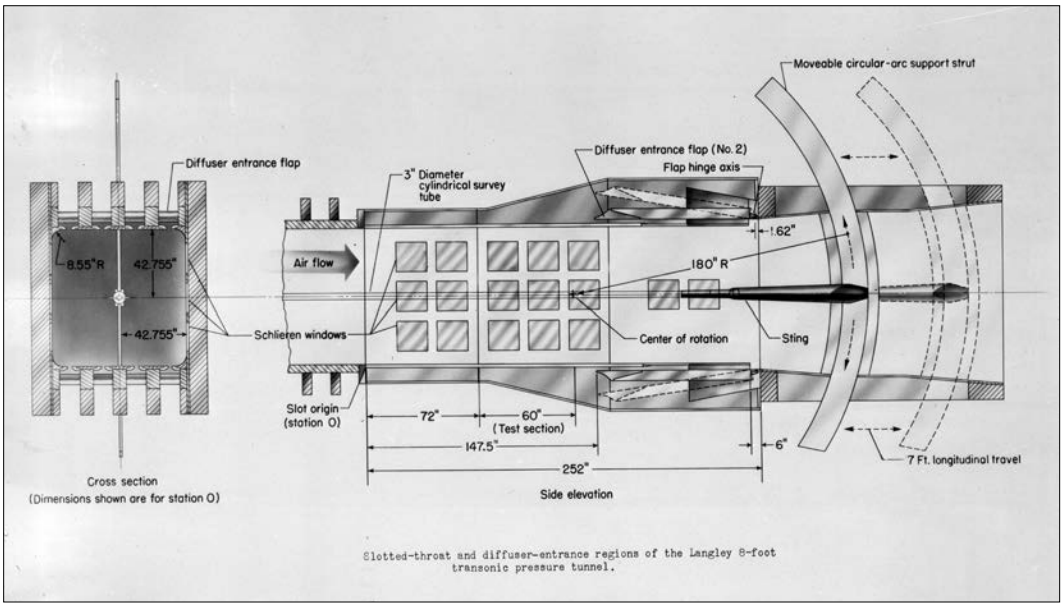
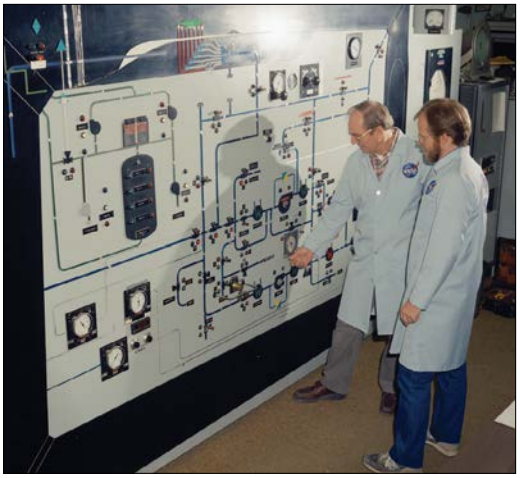


Diagram showing the test section of the 8-Foot Transonic Pressure Tunnel. (Image credit: NASA LRC-1979-B701_P-05316)



The Transonic Pressure Tunnel's complex pressurization and boundary layer removal systems were managed from this 7-foot-high panel, seen here in 1984, on the control room's opposite wall. (Photo credit: NASA LRC-1984-B701_P-02550)

Looking downstream through the Transonic Pressure Tunnel's test section in 1988. Note the sting support, multiple observation windows, and slots in the floor and ceiling, as well as the unusual quarter-round fillets in the corners. (Photo credit: NASA LRC-1988-B701_P-11585)

TRANSONIC DYNAMICS TUNNEL

This 1997 aerial view of the Transonic Dynamics Tunnel shows its current configuration. Modifications since its opening in 1960 have made little difference in its external appearance. (Photo credit: NASA LRC-1997-B701_P-02918)

SIGNIFICANCE

The Transonic Dynamics Tunnel (TDT) was the first large wind tunnel built by the NACA and NASA primarily to investigate aeroelasticity and flutter phenomena, and it is one of only a few non-hypersonic wind tunnels to employ test gasses other than air on a regular basis. This tunnel resulted from a major rebuilding of the 19-Foot PT, changing an obsolete tunnel into an excellent specialty tunnel that has proved to have capabilities that extend well beyond those originally envisioned, including the ability to simulate the atmospheres of other planets. In recent years, the TDT has hosted tests of sophisticated aircraft control concepts, and it is a vital venue for the evaluation of advanced computational fluid dynamics codes for both fixed- and rotary-wing aircraft.

DESCRIPTION

The TDT, Building 648 in Langley's East Area, is the result of an extensive modification of the 19-Foot PT, and it occupies the same area, although its footprint is larger. The TDT is a large, closed-circuit, variable-pressure wind tunnel consisting of a heavy-gage, arc-welded steel shell ringed with structural-steel hoops. The pressure shell has a circular

cross section throughout with four mitered corners, and the slotted-wall test section has a square cross section with a chamfer in each corner. The corner rings, as well as some others, are of heavier construction that transfers the weight of the tunnel to support legs, which rest on concrete foundations and pilings. A large plenum encloses the test section and serves as the pressure vessel around it. Approximately one-half of the circuit was originally part of the 19-Foot PT, with the remainder being new construction that was very similar in style to the older tunnel. As with the 19-Foot PT, this design minimized penetrations through the pressure shell to simplify its construction and improve its integrity. Unlike the 19-Foot PT, which operated under positive pressure, the TDT operates over a pressure range of 0.034–1 atmosphere (0.5–14.7 psia).[270]

The TDT was specifically designed to investigate aeroelasticity and flutter, particularly in the transonic flight regime, and it has the capability of operating with either air or a "heavy gas" as its test medium. While the TDT's original heavy gas was dichlorodifluoromethane (CCl_2F_2), more commonly known as Freon-12 or R-12, environmental concerns and a ban on R-12 production led Langley to rebuild the TDT's gas system to use tetrafluoroethane ($C_2H_2F_4$), also known as R-134a, in 1997–98. The facility has all the equipment needed to handle and store the R-134a on-site. Approximately one-half of the three-story brick building along the tunnel's northwest side houses the necessary vacuum pumps, compressors, and heat exchangers, along with the gas system control room, model-preparation shops, and office areas for the TDT. The welded steel storage tanks, which store the R-134a under pressure in liquid phase, are located at several places under the tunnel.[271]

A second building located in the central courtyard houses the tunnel's extensive array of electrical equipment that furnishes power to the drive motor and gas-handling equipment, as well as general service to the facility. It includes a control room where operators monitor the electrical system and communicate with the utility company regarding power needs and schedules. The TDT's drive motor is enclosed in a 165-foot-long nacelle mounted in the tunnel's back leg. The motor, originally rated for 20,000 horsepower but rewound to yield 30,000 horsepower in 1985, turns a 47-blade fan near the nacelle's nose. One row of adjustable pre-rotation vanes and two rows (one adjustable, one fixed pitch) of anti-swirl vanes surround the fan, and a smoothing screen is located near the nacelle's end. The drive train also includes an eddy-current brake for revolution control within ±0.25 percent. This drive system provides adjustable air speeds of up to Mach 1.2 in R-134a or air.[272]

The 16-foot-square test section has slots on all four walls and chamfers along its corners, giving it a distinctive cross section. Its floor can be hydraulically lowered to the same level as the second-floor model shop, where a large pressure door and continuous floor allow model transfer directly to and from the shop and tunnel. With the floor raised, personnel access is through an airlock from the building's third floor. The test section is mounted along the centerline of a 60-foot-diameter plenum, leaving ample room within the plenum for a control room, various model support systems, recording

equipment, and the test section floor elevator. A gate valve at its inlet and a butterfly valve at its outlet can be closed to seal the test section from the rest of the tunnel. When using R-134a, these valves allow the gas to be exchanged for air in the test section without an exchange in the whole tunnel, reducing access times between test runs by up to 75 percent. A vertical blade at the test section's exit supports an adjustable sting support. Sidewall and floor turntables are available to support semi-span and ground-based models, and the TDT utilizes a unique cable mounting system to give aeroelasticity models virtually complete freedom of motion. For tests involving gusts around a model, two sets of oscillating vanes with independently adjustable amplitudes and frequencies can be mounted in the sidewalls to disturb the flow.[273]

A wide variety of instruments can be connected to the TDT's data acquisition system to measure model position, forces, pressures, strains, and accelerations at rates of over 1,000 samples per second per channel. The system's computer not only captures this data, but also performs several online data-analysis routines for operators and test engineers.

The tunnel's control room, located within the plenum, is contained in a 15-foot-diameter by 32-foot-long pressure cylinder that is suspended alongside, but not mounted to, the test section. Its entrance is next to the outer door of the test section airlock, and its environment is the same as that of the adjacent building, regardless of the gas and pressure in the plenum. A set of windows in one wall of the cylinder aligns with a matching set in the test section wall. This arrangement helps maintain the integrity of the cylinder, and it serves a second safety purpose as well. In the event of a catastrophic model failure, a fairly common event during flutter tests, the test section wall windows can serve as a sacrificial shield against flying parts, thereby protecting the cylinder's windows and its occupants. All TDT operations are directed from here, though the heavy-gas system is actually controlled in a separate control room elsewhere in the facility. When built, the TDT also featured a small observation dome that protruded into the test section exit. As with the control room, this dome and the passage to it had to be sealed from the plenum. An observer could stand near the top of a ladder with his head inside the dome to witness tests. The view was excellent, but its hazards outweighed any benefit, and the dome was soon abandoned. Interestingly, it remained in place until 1997, when it was finally removed during a major renovation project.[274]

The 19-Foot PT's diffuser was lengthened considerably with new construction during the TDT conversion to obtain the correct flare for transonic operation. The back leg was similarly lengthened, and a new second leg, along with mitered turns 1 and 2, was installed. Turn 2 includes a safety screen to catch any part shed from the model before it can strike the fan. All corners are fitted with airfoil turning vanes. Downstream from the nacelle, turn 3 includes a two-row set of cooling coils. Water circulates through the coils and a cooling tower to remove much of the heat generated by the motor and fan. Although it is not controlled by a thermostat, these coils generally maintain the tunnel temperature around 105°F, but this can be as much as 140°F during tests at the highest Mach and dynamic pressure ranges. The 54-foot-diameter third leg and turn 4 form the

settling chamber, with the contraction into the test section starting immediately after turn 4. At this same point, the shell of the plenum diverges from the tunnel's shell.[275]

Another of the TDT's unique features is a set of four 36-inch-diameter bypass ducts that connect the plenum to the back leg of the tunnel, downstream from the fan. Each has a quick-acting valve that is normally closed. In the event that a high dynamic pressure begins to induce suspicious or divergent oscillations in the model during a test, an observer in the control room can press a handheld button known as the "chicken switch" to open these valves. Higher-pressure air from the back leg then flows into the plenum to raise its pressure, thus rapidly reducing the Mach number and dynamic pressure in the test section. The tunnel originally had two bypass ducts, but two more were added about 1965 to improve the response time. This safety feature has prevented the loss of many models.[276]

The heavy gas reclamation system (HGRS) is located in the northern half of the three-story equipment, shops, and office building. Operators in the heavy gas control room on the second floor, which features a large graphic display of the system, control all aspects of the HGRS as directed from the tunnel's control room. Also on the second floor are six 8,500-cubic-feet-per-minute, screw-type vacuum pumps and a five-stage Clark reciprocating recovery compressor. The first floor contains heat exchangers to cool and condense the R-134a for storage as a liquid, along with filters to purify it. Originally atmospheric air was passed through a desiccant dryer and to the tunnel when needed as the test medium, and the vacuum pumps exhausted it back to the atmosphere afterward, but the source was changed to the center's compressed air system during the gas-conversion project. This yielded a higher flow, a lower dew point, and quicker exchanges between air and the heavy gas. To minimize contamination, an air-to-heavy-gas or heavy-gas-to-air exchange requires that the tunnel, or plenum if isolated, be completely evacuated of one gas before the other can be introduced and brought up to the desired pressure.[277]

HISTORY

As discussed in the 4.5-Foot Flutter Tunnel (FT) and 26-Inch Transonic Blowdown Tunnel (TBT) sections, problems with uncontrolled, frequently divergent oscillations in aircraft structures, known as flutter, had been experienced since aviation's early days, but the cause and nature of the phenomenon remained obscure for decades. British researchers McKinnon Wood and Horace Lamb began experimenting in a Farnborough wind tunnel about 1926, and they developed the first scale-factor rules to obtain dynamic similarity between flutter models and full-size airplanes within a year.[278]

Increased speeds and changes in aircraft materials and construction during the 1930s and 1940s brought about an increase in flutter incidents, making it clear that serious research in the area of what became known as aeroelasticity was badly needed. At Langley, one group in the newly formed Vibration and Flutter Section (VFS) under theoretical physicist Theodore Theodorsen and empiricist Arthur A. Regier built the

FT, Langley's first flutter-specific facility and its first to use a heavy gas, in 1945. The FT could reach a speed of Mach 0.8. Theodorsen theorized, and Regier agreed, that flutter problems would get progressively worse as speed increased into the supersonic regime, but they could not validate this in the subsonic FT.[279]

Another group under Albert von Doenhoff and Laurence K. "Larry" Loftin, Jr., in the Full-Scale Division (FSD) also began to investigate flutter about this time independently from the VFS team. Loftin in particular did not believe that the VFS team's data supported its conclusion about flutter continuing to increase with speed. Von Doenhoff and Loftin built the TBT, which had slotted test section walls and could reach Mach 1.45, considerably higher than the larger FT, in 1950. This proved to be a vital difference because the TBT could explore the entire transonic speed range. Loftin and his team soon concluded that this transonic speed range was the most critical one for flutter. For reasons not then understood, but presumed to involve the highly complex mix of sub- and supersonic flows experienced, the speed where flutter would start to occur in a model seemed to drop around Mach 1 and actually decrease somewhat more at purely supersonic speeds.[280]

The two groups remained at odds over how and when flutter peaked in the early 1950s, and Regier proposed the construction of a new, larger tunnel for flutter testing that would incorporate everything learned from FT and TBT operations in 1951. His proposal stated several specific requirements:

- The tunnel should be as large as possible to accurately simulate model details, such as control surfaces.
- The tunnel should be capable of operating over a wide density range to simulate different altitudes.
- The tunnel should use a heavy gas such as R-12.
- The tunnel should be capable of speeds of up to Mach 1.2.

After considerable debate over what would clearly be a complex and expensive facility, Langley engineers concluded that it would be practical to convert the 19-Foot PT into a tunnel that met Regier's specifications, and the Transonic Dynamics Tunnel project was authorized in 1954.[281]

As the description above suggests, the TDT is a complex tunnel, with the most complex portion being the HGRS. Unlike the earlier heavy-gas tunnels, the TDT would reclaim and reuse its R-12 instead of releasing it to the atmosphere. The HGRS was expensive, but the large volume of gas needed to fill the TDT made it economically attractive. At the time, R-12's environmental effects were not appreciated.

In typical Langley fashion, the engineers decided to build a pilot tunnel to validate and refine the TDT's design. Three questions in particular needed answering: 1) would the 19-Foot PT's existing diffuser work well at the TDT's higher speeds, 2) could the test section's Mach number be quickly reduced in case a model became unstable, and 3) what was the optimum slot configuration? To address these concerns, B. H. Little, Jr., and James M. Cubbage, Jr., built a $^1/_{24}$-scale model of the TDT's core components.

This 8- by 8-inch blowdown tunnel successfully provided the needed data. Tests in it refined the test section, slot, and reentry section design; proved that a new diffuser with a 10-degree flare would be much more efficient than the existing 6.4-degree flare; and demonstrated that a valved bypass duct from the test section plenum to the settling chamber could reduce the test section Mach number very rapidly. These design elements were all incorporated into the TDT's design.[282]

Actual demolition and construction began in 1955, and the process took five years to complete. The project had five major components:

- Demolition of the 19-Foot PT's northern portion, including its test section; drive motor, fan, and nacelle; duct; and any unneeded equipment
- Fabrication and erection of the new plenum, bypass ducts, diffuser, motor nacelle, and tunnel shell
- Fabrication, erection, and connection of the new test section; control room, including control and data acquisition equipment; model support hardware; and other items inside the plenum
- Installation of the new drive system and associated electrical equipment
- Construction of the office building addition and installation of the HGRS equipment, piping, and controls

Contractors completed the conversion in 1959, and the TDT team, led by Robert Boswinkle, Jr., began to shake down and calibrate their new tunnel, tasks they essentially completed early in 1960.

The TDT's completion came none too soon. In September 1959 and March 1960, two new L-188 Electra airliners broke up in flight and crashed. In both cases, investigators realized the planes had each lost an entire wing! Within two months, engineers at both the builder and Langley began to suspect an unusual phenomenon called propeller-whirl flutter of having caused the accidents. Analysis and tests of an elaborate, dynamically scaled Electra model in the TDT indicated that whirl flutter could not normally reach damaging levels, but the new turboprop engines had very different mounts than those of their predecessor piston engines, and the investigators focused on possible mounting problems. Tests revealed that weakened elastomeric mounts on the outboard engines could allow whirl flutter to develop at a frequency that matched a resonant bending frequency of the wing. As one TDT test run with weakened mounts dramatically demonstrated, the combination had disastrous effects. One wing separated from the model exactly as the wings had from both planes before they crashed. The builder immediately initiated a recall program to strengthen the engine mounts, and over 1,000 L-188s have since seen over four decades of service without another failure of this kind. While no hard data exist, some have claimed that this, the TDT's first test program, more than justified its cost.[283]

Since that auspicious beginning, researchers have investigated virtually every kind of aeroelasticity issue, and the test projects conducted in the TDT have involved almost every type of aircraft and spacecraft built since 1960. Many programs involved flutter

clearance tests to make sure an airplane will not experience flutter anywhere within its operating envelope. Other programs have been more research-oriented, and most of these have sought to generate data to improve the flexibility and accuracy of computational fluid dynamics (CFD) software. The TDT's extensive data acquisition and computational capabilities make it an ideal venue for CFD code validation, and most test programs now include some aspect of code validation or development.[284]

The TDT also has been used for the aeroelastic evaluation of spacecraft and rocket boosters. Booster-payload "stacks" can be very susceptible to vibration and flutter from such things as engine combustion instability and shear loads from crosswinds, especially near Mach 1. Even before launch, space boosters can be damaged on the launch pad by ground winds. As with all aerospace structures, boosters are flexible, and it is possible for wind at the right speed to make a stack on the pad oscillate at a resonant frequency and structurally fail or strike its service structure. All concerned need to know that any stack is stable in both its fueled and empty conditions. Detailed, dynamically scaled models of numerous vehicles and service towers have been tested using the tunnel's floor turntable to obtain data at every wind direction.[285]

With its heavy-gas and variable-pressure capabilities, the TDT is a good venue for evaluating the performance of space probes entering the atmospheres of other planets. Such entries typically use a parachute after the vehicle has slowed enough for safe deployment, but atmospheric conditions vary widely between planets, and the parachute designs vary as well. Parachute tests in the TDT have required test conditions that simulated atmospheres ranging from the sparse one of Mars to Jupiter's deep, dense one. These tests not only examine retarding power, but deployment and flight stability as well.[286]

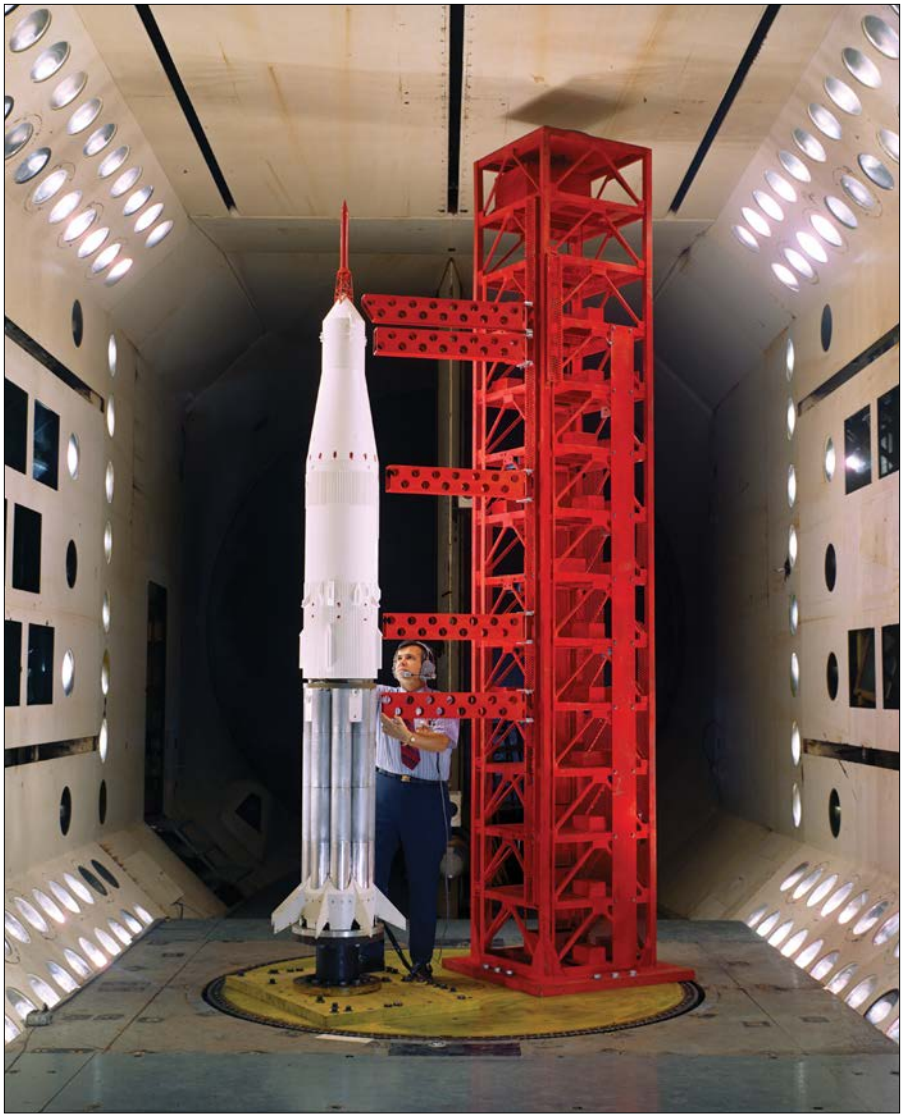
While flutter has always been dreaded, some recent investigations have studied ways that active control systems might use aeroelastic effects in a beneficial manner. The concept is still in its infancy, but the success of current fly-by-wire control systems that safely manage unstable airplanes to achieve outstanding maneuverability makes the idea of extending the concept to manage perhaps dozens of control surfaces or even wings with flexible leading and trailing edges—somewhat reminiscent of the Wright brothers' Flyer—increasingly viable. Researchers at the TDT have participated in these studies for more than two decades.[287]

Helicopter development has historically used much less wind tunnel time than fixed-wing aircraft, but aeroelastic testing of rotor blades is a critical part of their development. The TDT is well equipped for such testing, and the staff has developed a generic test platform known as the Aeroelastic Rotor Experimental System (ARES). Any blade design can be attached to ARES's rotor hub, and the model is thoroughly instrumented to measure all significant rotor parameters. The ARES model has been modernized several times to increase its capabilities and keep it up to date.[288]

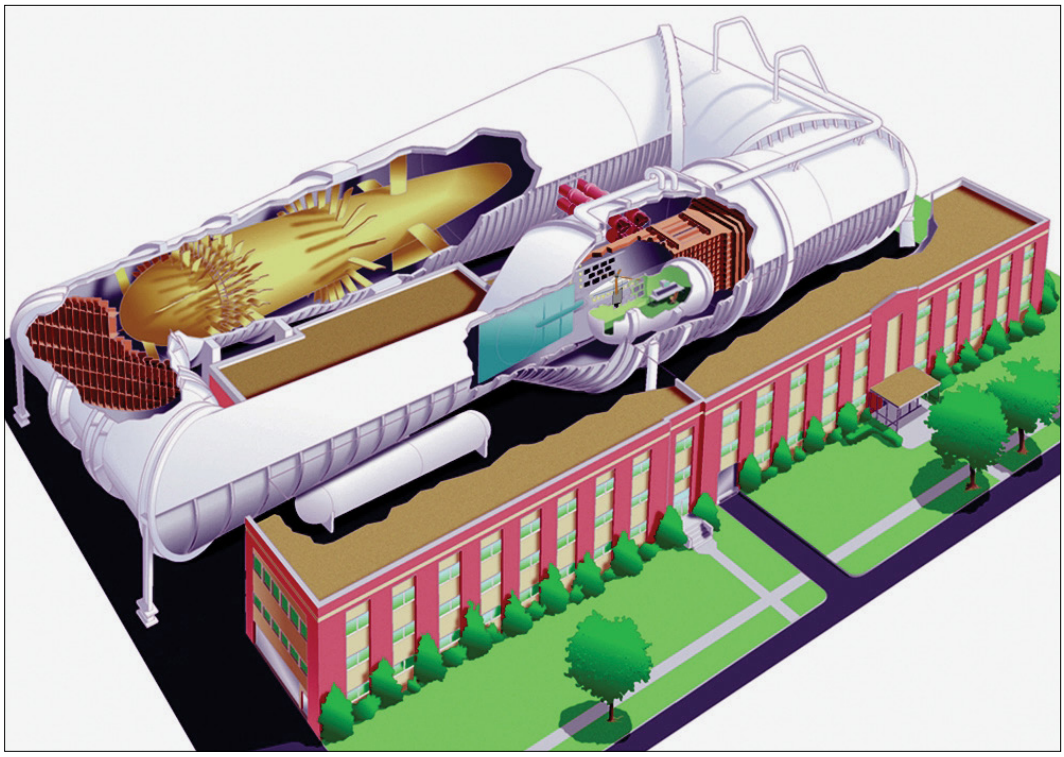
The TDT has also been modernized several times. The most significant of these was the conversion from R-12 to R-134a for heavy-gas testing during 1996–97, but other modernization programs have improved gas handling; upgraded its control,

data acquisition, and drive systems; and installed new model mounts. Plans exist for additional work as well.[289]

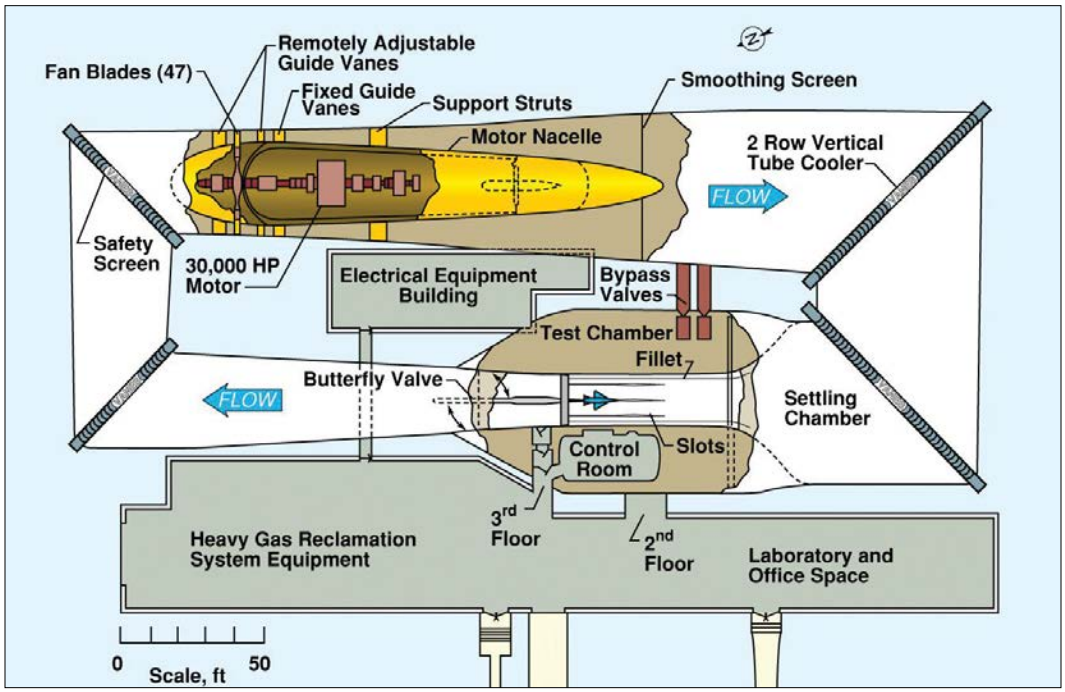
Where its predecessor, the 19-Foot PT, had proven to be ill-suited to changing research needs when it opened, the TDT was ideal for its tasks, and it has been a well-used facility for almost 50 years. Because of its unique capabilities, versatility, and ongoing modernization programs, the TDT remains in active service.



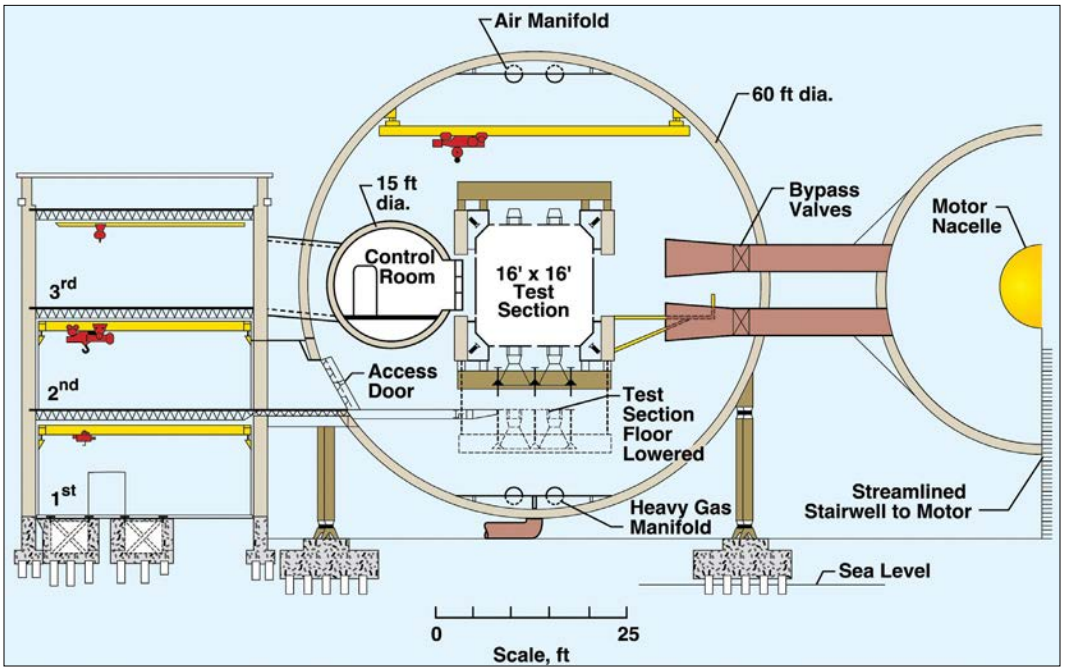
Wind blowing against rockets and service structures can generate serious vibration problems while a missile is on the launch pad. In this 1971 photograph, an Apollo-Saturn I-B stack is set up on the Transonic Dynamics Tunnel's turntable for on-pad testing. The turntable allows testing at all wind directions. (Photo credit: NASA LRC-1971-B701_P-08904)



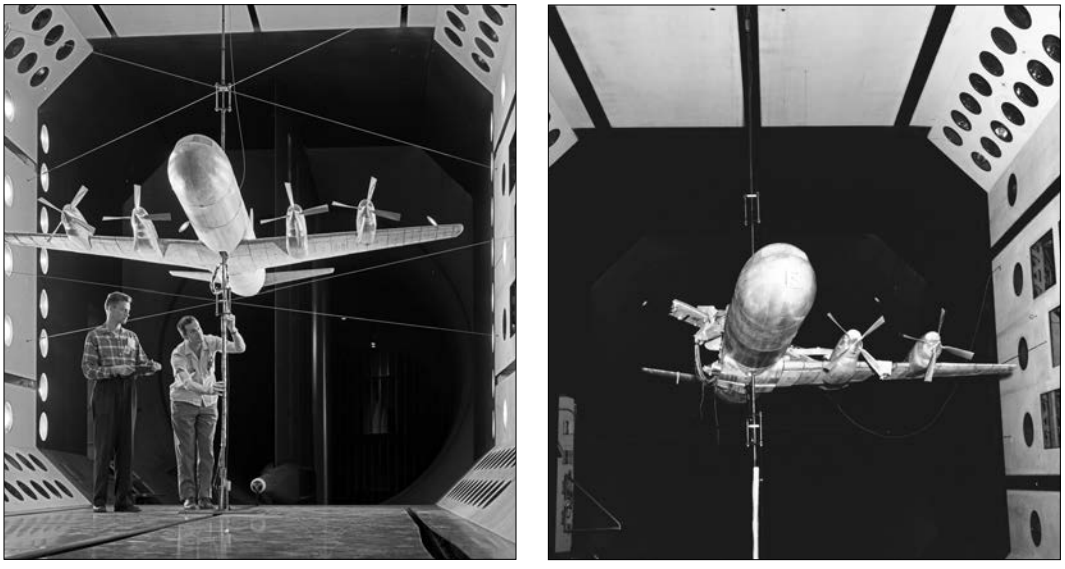
A cutaway drawing of the Transonic Dynamics Tunnel showing one set of turning vanes, the motor nacelle, test section, control room, and plenum. The tank under the tunnel is one of the heavy-gas storage tanks. The TDT has one of the largest motor nacelles ever installed in a wind tunnel. The flow is clockwise. (Image credit: NASA LaRC-TDT-2)



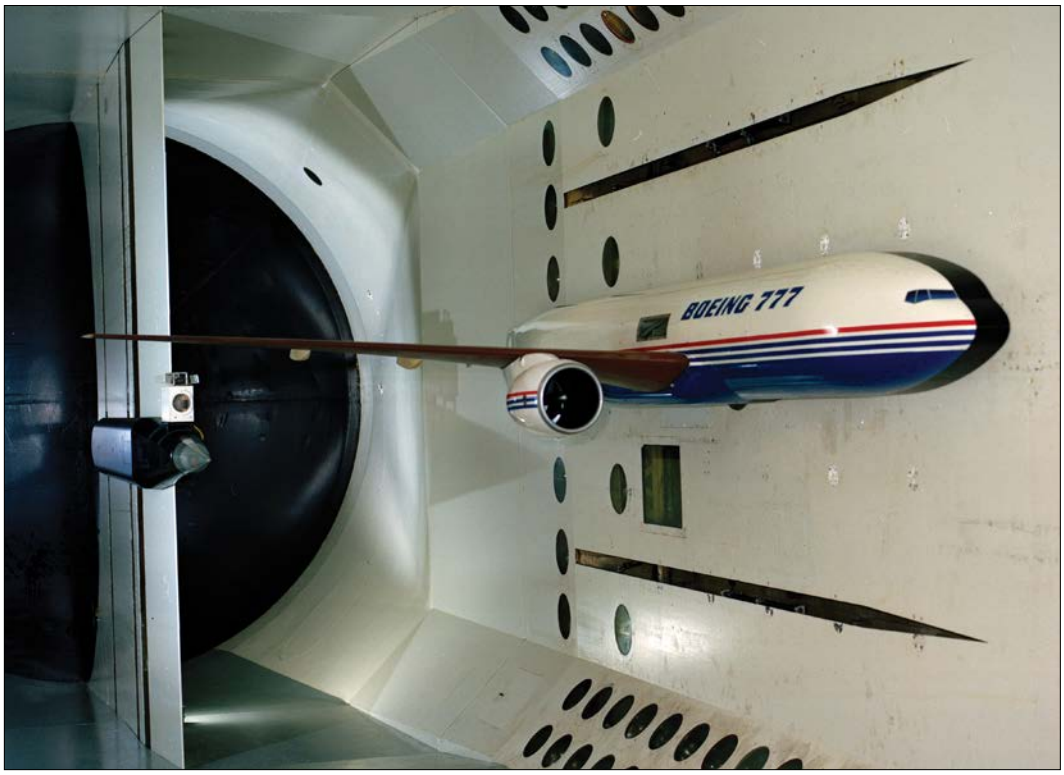
This plan drawing identifies the Transonic Dynamics Tunnel's major components. The quick-opening bypass valves that can rapidly reduce the test section Mach number are a unique feature of this tunnel. Opening them has prevented the destruction of many models that started to oscillate in an unstable manner. The TDT now has four bypass valves. (Image credit: NASA TM X-1130)



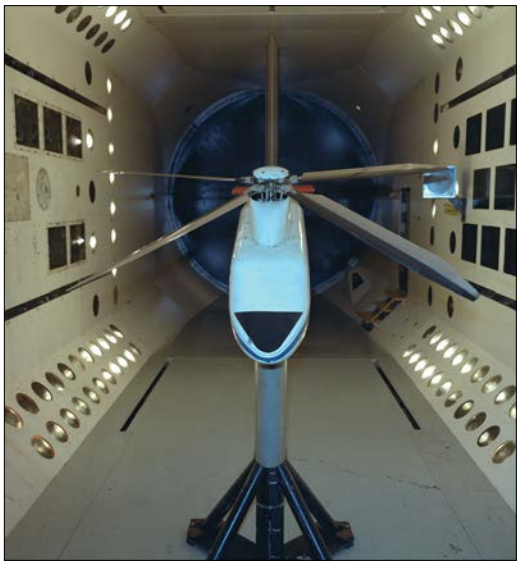
This section drawing, looking downstream through the test section of the Transonic Dynamics Tunnel, details its arrangement inside the plenum. Note the sealed control room, bypass valves, and retractable test section floor. (Image credit: NASA LaRC-TDT-4)



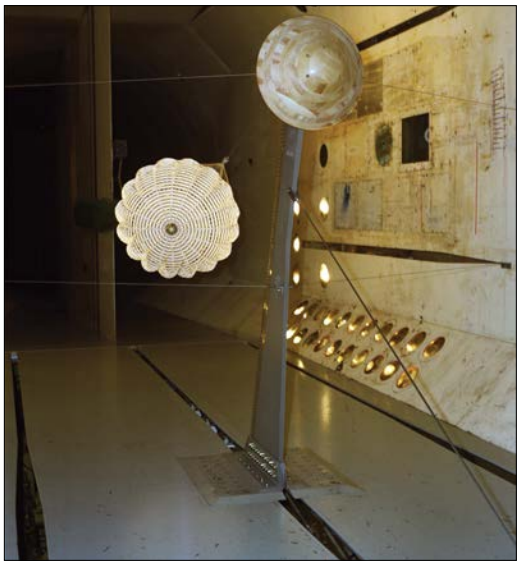
The Transonic Dynamics Tunnel's first test program in 1960 investigated wing failures on two L-188 Electra airliners. Tests of this dynamically scaled Electra model dramatically confirmed that propeller-whirl flutter caused the failures and crashes. All the planes were quickly modified, and there have been no subsequent failures of this kind in over four decades of service. Note the pole suspension through the model's center of mass that allowed it complete elastic freedom. (Photo credits: NASA LRC-1960-B701_P-02562 and NASA LRC-1960-B701_P-04772)



A semi-span model of a B-777 mounted on the Transonic Dynamics Tunnel's sidewall in 1992 for wing and engine flutter testing. Though not used for this test, the vertical blade and fixture for sting mounts is clearly visible at left. (Photo credit: NASA LRC-1992-B701_P-08250)



The Aeroelastic Rotor Experimental System helicopter model in the Transonic Dynamics Tunnel in 1985 for tests of a rotor blade design under development. The model is mounted farther upstream than usual for safety. Should a blade fail and separate during operation, it would be unlikely to strike the rectangular windows on the left and endanger the control room occupants. (Photo credit: NASA LRC-1985-B701_P-12990)



The parachute for the Galileo probe, seen here in 1983, into the Jovian atmosphere saw extensive testing in the Transonic Dynamics Tunnel, which can simulate various planetary atmospheres. Similar tests have been conducted in the TDT for missions to other planets as well. (Photo credit: NASA LRC-1983-B701_P-03654)

7-INCH HIGH-TEMPERATURE TUNNEL

This humble building housed the 7-Inch High-Temperature Tunnel. Note the tunnel's flared exhaust. (Photo credit: Greg Mekkes, NASA)

SIGNIFICANCE

The 7-Inch High-Temperature Tunnel (7-Inch HTT), originally named the 7-Inch Mach 7 Pilot Tunnel, was built to validate NASA's design for the proposed 8-Foot High-Temperature Structures Tunnel. After the 8-foot tunnel became operational, this tunnel continued in service for many years as a venue for designing tests intended for the larger tunnel and potential modifications to it, roles that enhanced both safety and economy.

DESCRIPTION

The 7-Inch HTT was a 1/12–scale model of the 8-Foot High Temperature Structures Tunnel. It was located across Moffett Road from the larger tunnel and occupied Building 1264 in Langley's West Area. The building was a rectangular, wood-framed structure with asbestos-cement siding and a corrugated-metal roof.

The tunnel itself consisted of a combustion chamber, nozzle, test chamber, diffuser, air ejector, and mixing tube/exhaust, all arranged linearly and coaxially. Its nominal total length was 34 feet, but the tunnel expanded about 1 inch during operation. It was constructed primarily from steel and stainless-steel alloys. To accommodate thermal

expansion, all of the tunnel's supports were flexible, except for a single anchor at the test chamber. The air and fuel connections had flexible couplings as well.[290]

The combustion chamber burned methane (CH_4) in air, and the air was routed to it from a high-pressure bottle rack outside the southwest side of the building. Compressed air was supplied by Langley's central utilities system and boosted to 6,000 psi for storage in the bottle rack. Methane arrived via a commercial utility pipeline, and its pressure was similarly increased for storage in its bottles. Remotely operated valves in these systems were controlled from the tunnel's control panel. Almost all this piping was aboveground. Incoming air cooled the combustion chamber by passing through an annular space between the outer case and an inner, finned liner.

Burning methane in air produced a test gas known as "vitiated air," primarily nitrogen, carbon dioxide, and water vapor at temperatures between 2,000 and 3,340°F. Vitiated air was adequate for materials testing, but an oxygen-enrichment system was needed for engine tests. The test gas passed out of the combustion chamber through an axisymmetric nozzle and entered the test chamber as an open jet, 7.5 inches in diameter. Changing the temperature and/or static pressure allowed actual test speeds to be varied from Mach 6.5 to 7.7.

The test chamber was a sphere, with a "pod" on the bottom that contained the model injector. Models were mounted on a sting. Flow from the nozzle exit entered on one side and exited into the diffuser on the opposite side. Designed primarily as an open-jet chamber, it had additional components that allowed it to be run with a closed jet to compare the two modes. Two sides contained circular viewing windows that could be opened for model access. The test chamber was hermetically sealed, as tests were run at reduced pressures to simulate altitudes of 50,000 feet and above.

The diffuser included an air ejector about 4 feet downstream from the test chamber. High-pressure air injected through an annular slot induced a vacuum on the test chamber and, by mixing with the test gas, cooled it somewhat prior to its exhaust to atmosphere just outside the building's northeast wall. Test runs typically lasted between 1 and 1½ minutes. All aspects of each test were manually controlled from a panel in an adjacent room in Building 1264.

When the 8-Foot High Temperature Structures Tunnel was being considered for scramjet testing, the concept was first tried and evaluated in the 7-Inch HTT. This required the addition of hydrogen and oxygen systems for the model engine. The majority of these tanks, pipes, pumps, and valves were installed outside the building.[291]

HISTORY

When the 8-Foot High-Temperature Structures Tunnel was proposed in the late 1950s, the use of combustion power had already been proven in the 9- by 6-Foot Thermal Structures Tunnel, which had recently (1957) entered service. Though successful for evaluation of materials for high-supersonic aircraft, the 9- by 6-foot tunnel's Mach 3

speed was insufficient to fully test materials in conditions simulating atmospheric entry from orbit. Calculations supported an extrapolation of the concept to around Mach 7, but Langley engineers decided to build a small pilot tunnel to verify the theory. It was a common, conservative, and fruitful technique frequently employed at Langley when venturing into uncharted territory involving major investments. Thus was born the 7-Inch Mach 7 Pilot Tunnel, later known as the 7-Inch High-Temperature Tunnel.

The engineers chose to build it in 1/12 scale, which made the nozzle exit 7.5 inches in diameter. They proportionally followed the proposed design for what would be the 8-Foot High-Temperature Structures Tunnel as closely as was practical, including a novel "pod" beneath the test chamber to house the model-injection mechanism within the chamber's pressure shell and an air ejector to control test chamber static pressure. Also like the proposed tunnel, the pilot would be a linear design with an axisymmetric nozzle at the exit of its combustion chamber and a flared exhaust to atmosphere. Its 34-foot length was closer to 1/8 scale, but the difference was in the combustion chamber, not the aerodynamic portion of the tunnel. The combustion chamber, along with the methane and high-pressure air supplies, was designed to perform in the desired manner, but the smaller volumes involved dictated a different physical layout from that projected for the 8-foot tunnel.[292]

As with most pilot facilities, this one was expected to be used for only a short time to validate the design for the permanent tunnel. Accordingly, Building 1264 was built much like the military's "temporary" structures, with a wooden frame and asbestos-cement siding. In this case, a corrugated-metal roof was installed. The building, measuring approximately 30 by 30 feet, enclosed all but the exhaust flare of the tunnel and a separate control room. Fuel and air storage and piping was outside.

Exactly when this tunnel first ran is unknown, but it was probably during 1959 or 1960, since construction of the 8-foot tunnel's foundation began in 1959. As intended, its checkout and calibration process resulted in the refinement of a number of details that were incorporated into the larger tunnel. The engineers also learned much about the operating parameters and developed safe techniques for running a tunnel under such extreme conditions—knowledge that transferred to the 8-foot tunnel.

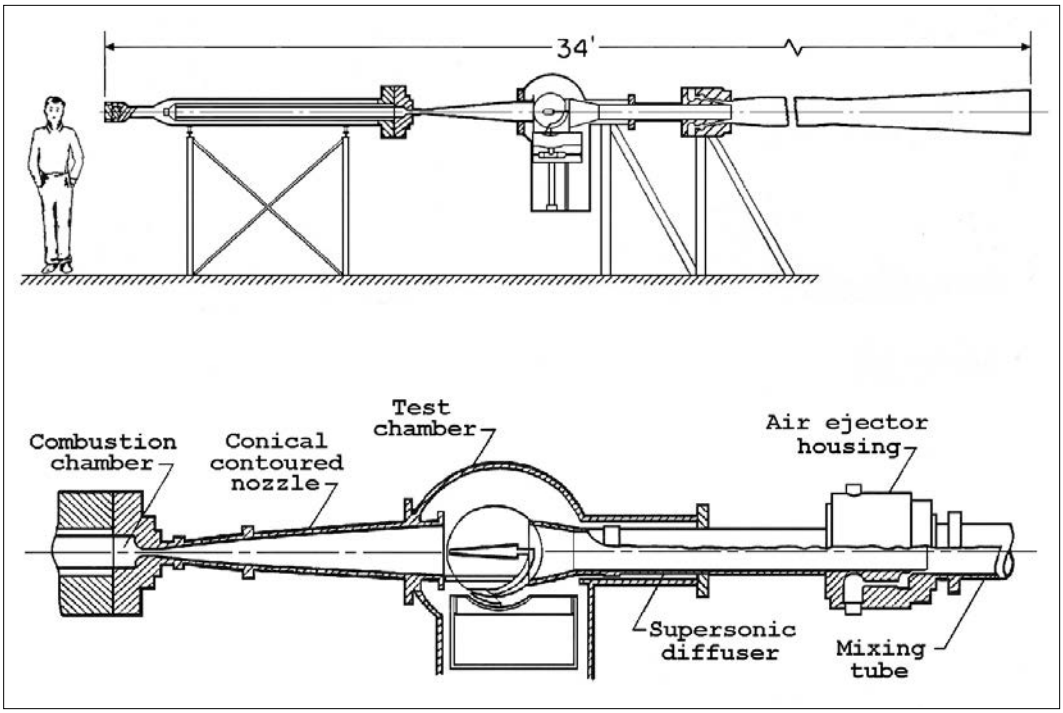
When the 8-Foot High-Temperature Structures Tunnel went online in 1965, the researchers using it decided to retain the 7-Inch HTT in case it might be useful in solving unanticipated problems. It was a wise decision, as the tunnel became a low-cost way to develop model support structures and test protocols before committing large sums on tests in the 8-foot tunnel. Such pilot tests not only saved thousands of dollars, but they also identified potential safety problems and solutions.[293]

A similar scenario unfolded in the 1980s, when discussions about modifying the 8-foot tunnel to accommodate propulsion testing began. Once again, the 7-Inch HTT was used to test the concept and refine the design of the modifications. The necessary hydrogen and oxygen systems were added to furnish model-engine fuel and increase the oxygen content in the test stream, and the test program demonstrated that the

design was sound. One set of tests went so far as to investigate the potential for liquid oxygen contamination from gaseous nitrogen intended to propel the oxygen into the combustor. As with earlier pilot tests in the 7-inch tunnel, the developed components scaled up to the 8-foot tunnel well. A second major modification of the 8-foot tunnel, adding a mixer and alternate nozzles for Mach 4 and 5, was likewise demonstrated in the 7-Inch HTT in the 1990s.[294]

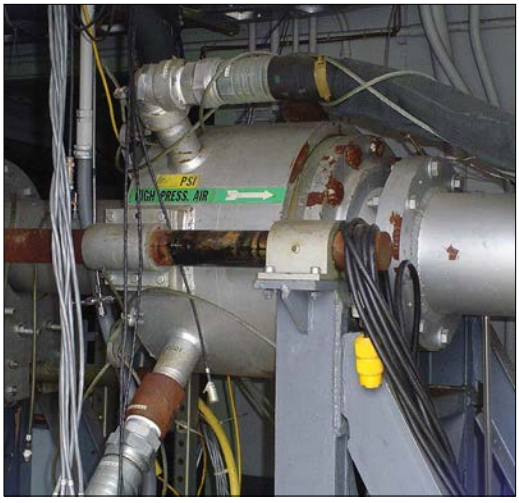
Like all high-pressure devices and systems at Langley, the 7-Inch HTT underwent scheduled inspections and recertification by the center's safety personnel. It had been built as a temporary facility, and some measures normally taken to reduce deterioration on permanent facilities were not included. Most piping was exposed to the weather, and the inspectors became increasingly concerned about its potential for rupture. They no doubt remembered how a pipe carrying air at a tenth the pressure had failed catastrophically at the 9- by 6-Foot Thermal Structures Tunnel in 1971 and did not want a recurrence. The tunnel's crew had maintained it well, but the inspectors finally refused to recertify it in 2004. With little justification for rebuilding the tunnel's systems, NASA demolished it in 2006. The staff of the 8-Foot High-Temperature Tunnel retained the little tunnel's key components. Should the need arise, they could form the basis of a reconstructed tunnel, but there currently are no plans for such a resurrection.[295]

Researchers conducted tests in the 7-Inch High-Temperature Tunnel from this small, but well-equipped, control panel, seen here in 2004. (Photo credit: NASA LRC-2004-B701_P-01620)



These drawings show the arrangement and size of the 7-Inch High-Temperature Tunnel. The lower drawing details the tunnel's core section and identifies its major components. These drawings predate the modifications made to enable propulsion testing. (Image credit: NASA TM-83301, Fig. 5)

This bottle rack, seen here in 1983, supplied high-pressure air to the 7-Inch High-Temperature Tunnel's combustion chamber and air ejector. (Photo credit: NASA LRC-1983-B701-P-04669)



An air ejector, seen here in 2005, controlled the static pressure in the 7-Inch High-Temperature Tunnel's test chamber. Compressed air entering via the radial pipes flowed through an annular nozzle to induce a partial vacuum in the upstream test chamber. (Photo credit: NASA LRC-2005-B701_P-01540)

8-FOOT HIGH-TEMPERATURE TUNNEL

An aerial view of the 8-Foot High-Temperature Tunnel in 1993. (Photo credit: NASA LRC-1993-B701_P-13120)

SIGNIFICANCE

The 8-Foot High-Temperature Tunnel, originally named the 8-Foot High-Temperature Structures Tunnel, is NASA's largest hypersonic wind tunnel and the largest tunnel primarily powered by combustion energy. Originally built to test materials under conditions simulating the high-speed, high-temperature conditions experienced by spacecraft reentering Earth's atmosphere, modifications have made it the premier facility for testing hypersonic air-breathing engines.

DESCRIPTION

The 8-Foot High-Temperature Tunnel (8-Foot HTT), which occupies most of Building 1265 in Langley's West Area, is a blowdown-type facility that exhausts to the atmosphere,

but instead of utilizing only compressed air as its power source, it adds to that heat energy from a large methane burner to produce speeds approaching Mach 8 and stagnation temperatures of up to about 3,600°F. About half of the tunnel is within a three-story, brick-and-metal building, but its flared exhaust diffuser extends about 150 feet north of the building. A concrete apron extends over 300 feet beyond the diffuser's end. Near the northeast side of the building is a rack of vertical, high-pressure gas bottles that store air at approximately 6,000 psi.[296]

The tunnel itself consists of a combustor, nozzle, test chamber, diffuser, air ejector, and mixing tube/exhaust, all arranged linearly and coaxially. Its nominal total length is 275 feet, but the length will vary depending on the nozzle used, and it expands about 1 foot during operation. It is constructed primarily from steel and stainless-steel alloys. To accommodate thermal expansion, all of the tunnel's supports are flexible, except for a single anchor at the nozzle. The air and fuel connections have flexible couplings as well.

The combustor, which burns methane (CH_4), consists of a fuel-injection rack/flame holder mounted inside a 3-foot-diameter, 30-foot-long circular duct. The fuel injector's original design consisted of concentric rings of tubes with multiple fuel-injection ports, but this was changed in 2001 to a design featuring horizontal bars with multiple injection ports, which provides better flow and improved ignition. Incoming air from the bottle rack flows through two concentric, annular channels that serve as the combustor's liner. This serves to cool the combustor wall and recover heat that would otherwise escape. The air then enters the combustor upstream of the methane injector. The assembly also includes a system that injects oxygen as necessary to give the vitiated-air (primarily nitrogen, carbon dioxide, and water vapor) test gas from the combustor adequate oxygen for the test engines to function properly.

Leaving the combustor, the test gas passes through one of several nozzle assemblies—some of which include a mixing box to introduce additional air that reduces the temperature and speed—and flows through the test chamber. The primary nozzle is designed to produce Mach 7, but a variety of assemblies are available to replace much of the nozzle's Mach 7 expansion section to produce Mach numbers of 4 or 5. The hottest portions of the nozzle—its inlet, throat, and primary expansion section—are transpiration-cooled. These sections are made by stacking hundreds of thin, stainless-steel laminations, each of which has portions of small air passages etched into it. When assembled, the stack forms the core portion of the nozzle. While the wall finish is smooth, it contains thousands of minute ports that admit air. The air forms a thin film that insulates the wall from the 3,600°F gas, cooling it more effectively than an internal water circuit. The cooling air becomes part of the test gas without contaminating it, and it also helps control boundary-layer formation.

To achieve Mach 4 or 5 speeds, the secondary section of the Mach 7 nozzle is replaced with a mixer, followed by a Mach 4 or 5 nozzle as desired. The 13-foot-long mixer has a conical inlet that expands to 4 feet in diameter. The inlet has numerous ports that

inject high-pressure air. This combination of air mixing with the flow and the expansion causes the mixer to act like a settling chamber into the downstream Mach 4 or 5 nozzle.

The test chamber approximates a 26-foot-diameter sphere with the 96-inch-diameter nozzle exit on one side and a 103-inch-diameter diffuser entrance directly opposite. It is fabricated of steel plate with heavy external stiffening ribs. Both sides feature multi-panel observation windows of high-temperature glass, including ports suitable for schlieren photography. The top of the chamber is a removable hatch that bolts into place to form a hermetic seal. A crane above the hatch is used to insert and remove models. The test chamber's bottom, known as the "pod," is a vertical extension of the chamber, 18 feet high by 16 feet in diameter, which contains the elevator and model-mounting apparatus. Various mounting arrangements are possible to suit testing of material samples and operating scramjet engines, including a sting with ±20 degrees of pitch adjustment. Once stable flow has been established in the tunnel, the elevator can inject a model into it, or extract a model from it, in as little as 1 second. All fuel, control, and instrument connections to the model are routed through the pod to keep them protected from the hot gas flow.

During test runs, the static pressure in the test chamber is generally reduced to a pressure simulating 50,000 to 120,000 feet in altitude. This is accomplished by an air ejector mounted in the diffuser, downstream from the test chamber. Air injected here not only induces a partial vacuum on the test chamber, but it mixes with the exhausting gas to cool it somewhat before it is discharged to the atmosphere through a flared outlet. In operation, the exhaust resembles that of a large jet engine in velocity, temperature, and noise level. The roar, which can be heard several miles away, restricts the tunnel's operation essentially to daylight hours.

When the 8-Foot HTT was modified for scramjet testing, systems for hydrogen and oxygen were added, with the majority of their tanks, pipes, pumps, and valves located outside the main building or inside small auxiliary buildings. These systems, along with the tunnel and burner equipment, are managed from a control room near the test chamber in Building 1265. To ensure safety while dealing with such potentially dangerous gasses, an elaborate, multilevel key system is employed to ensure that no portion of any system can be engaged unless every device that supports it is known to be operating correctly. The same system prevents personnel from entering the tunnel unless all hazardous systems have been locked out.

Test runs typically take between 1 and 2.5 minutes, and they are now preprogrammed into computerized controls that manage the entire process, including gas flow, air ejection, burner ignition and flame control, model insertion and retraction, and all aspects of the model engine's burn.

HISTORY

The 8-Foot High-Temperature Structures Tunnel was the second large facility built at Langley for materials testing, the first being the 9- by 6-Foot Thermal Structures Tunnel (TST), which had entered service in 1958. The TST, while useful, could not generate Mach numbers and temperatures high enough to simulate the conditions a crewed spacecraft would encounter entering Earth's atmosphere from orbit. But the TST had proven the concept of heating high-pressure air with a large burner to produce a large volume of test gas, even if it consisted of combustion products instead of pure air, and engineers believed a similar but more powerful tunnel would generate the conditions needed. The design specifications called for Mach 7 flow at simulated altitudes between 50,000 and 120,000 feet and temperatures between 2,000 and 3,500°F. Test material panels needed to be close to full scale, which dictated a test jet at least 7 feet in diameter.[297]

Combustion power was the only practical choice. A tunnel of this size and speed would require a 1,000,000-horsepower drive, which was more power than a typical steam-electric generating unit of the day could produce. Compressed air from Langley's central utilities system could be stored at 6,000 psi in a large bottle rack and admitted to a combustion chamber during test runs. There, methane (CH_4) could be injected and burned to create a high-energy gas known as "vitiated air," which could then pass through a hypersonic nozzle and into a test chamber. From the test chamber, the gas could be routed through a diffuser to the atmosphere, and an annular air ejector in the diffuser could reduce the test chamber's static pressure. Calculations showed that the specifications could be met in this manner, but the temperatures involved, up to 3,600°F in the combustor and nozzle, meant that cooling the apparatus would be a challenging problem.[298]

Cooling was accomplished by using the incoming air as the coolant. Air entering the combustor passed through two annular passages in the cylindrical wall before it entered the chamber to flow through the methane injector. Thus, it absorbed considerable heat, cooled the wall, and returned that energy to the airstream. Air was also used to cool the hottest portion of the nozzle, but in a different manner. The nozzle employed transpiration cooling, where small jets of air flowing through a porous nozzle wall formed a thin insulating boundary layer that protected the nozzle. Aerojet Incorporated devised a way to make such a nozzle using hundreds of thin pieces that were stacked to form it. These pieces were etched stainless steel that, when assembled, formed tiny passages for the air that led to the inside surface. Each piece was slightly different to produce the correct nozzle contour and a smooth inner surface.[299]

Construction began in 1959, and the tunnel's first hot run occurred in August 1965. Ironically, the crewed space program had been one of its principal supporters, but the tunnel was not ready in time to test heat shields for the Mercury and Gemini capsules, and it performed only a little work for the Apollo spacecraft. It did, however, benefit numerous uncrewed programs and performed extensive testing of the Space Shuttle orbiter's reusable thermal protection system throughout the late 1960s and 1970s. During this period, the tunnel's operators learned much about the problems involved

with running under such extreme conditions. One of these involved cracks that began to form in the combustor's wall due to fatigue caused by thermal expansion/contraction cycles after only 50 runs. Different materials and design adjustments to improve cooling ultimately reduced the severity of this and other problems.[300]

In the mid-1980s, America decided to develop the National Aero-Space Plane (NASP), a hypersonic transport that might also serve as the basis for a second-generation, reusable spacecraft. A key element of the NASP project was the development of a large supersonic-combustion ramjet, or "scramjet," engine. It would require hundreds of test hours, and NASA engineers believed the 8-Foot TST could be modified to serve as an excellent scramjet test tunnel. The idea found favor, and the project was funded in 1988.

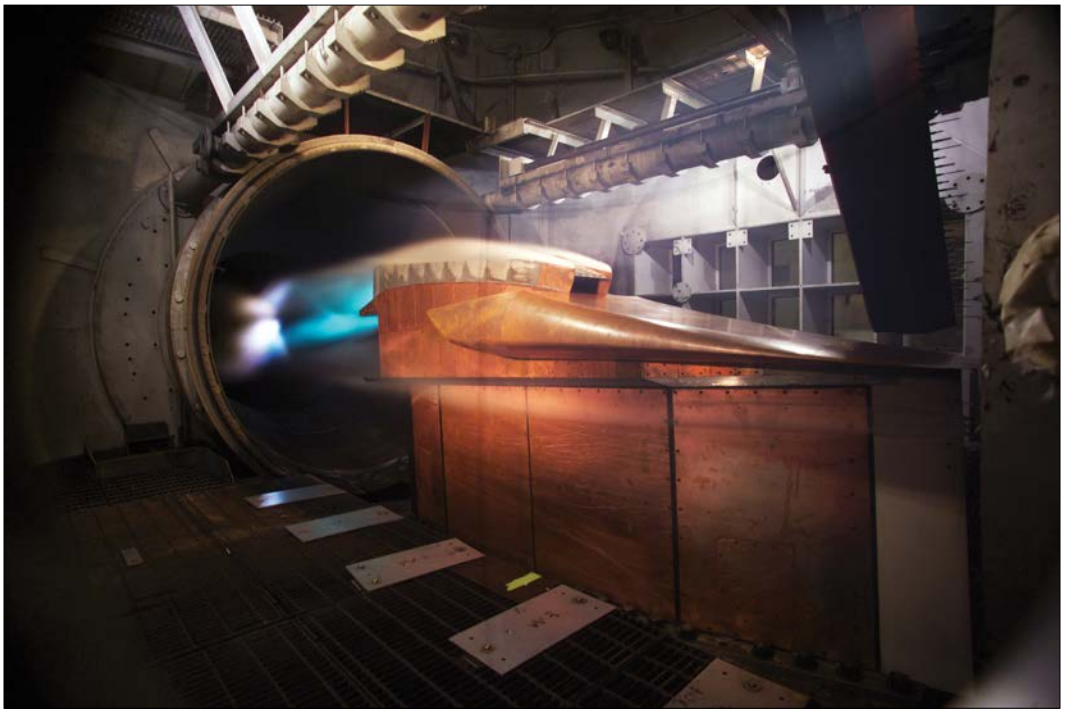
While the tunnel's basic design and operation would remain the same, several new systems were needed, particularly a fuel system for the model engines. Hydrogen was the fuel of choice, and a storage and delivery system was built to the building's northeast. A separate system to handle a silane-hydrogen mixture used to help start the model engines was installed as well. For the vitiated-air test gas to have sufficient oxygen to support combustion in the model, oxygen had to be added. The engineers decided to use liquid oxygen, and they designed an injector to introduce it immediately ahead of the methane injector. By controlling the flow rate, the oxygen concentration in the test section could be carefully controlled. For safety, the liquid-oxygen storage and handling equipment was located to the building's southeast, well away from the hydrogen area. A gaseous nitrogen system was installed to purge the hydrogen and oxygen systems at shutdown, and a flare stake was erected so that any residual methane or hydrogen could be safely burned off when necessary. The air-ejector also serves to evacuate hazardous fumes from the test section after each run. Engineers also installed an elaborate key-and-lock system manufactured by the Kirk Key Interlock Company to ensure that each of these systems could only be activated and the tunnel operated in a specified sequence that minimized hazards. A new computerized control system managed the test runs.[301]

The original high-pressure air storage bottles were replaced during 2000–01. The original bottles were fabricated from laminated steel walls welded to forged steel heads. Improved technology allowed the replacements to be one-piece, deep-draw forgings. A new methane injector was installed during this same period to obtain more-reliable ignition and improved flame stability.[302]

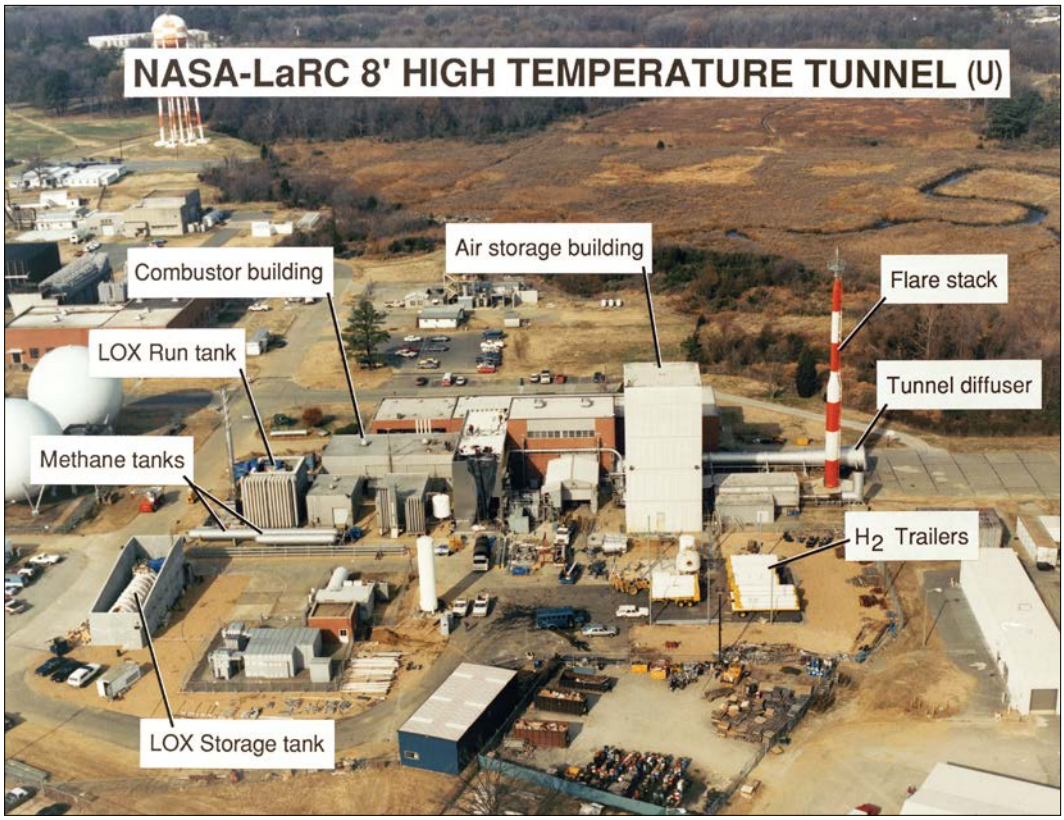
In 1996, equipment was delivered that allows the tunnel to operate at Mach numbers of 4 and 5, as well as 7. A cylindrical device known as a mixer can replace the downstream portion of the Mach 7 nozzle. Using a combination of expansion and the injection of additional air, the mixer serves as a settling chamber. A Mach 4 or 5 nozzle insert downstream from the mixer delivers gas to the test chamber. While the parts are interchangeable, the change-out process is complex and typically takes at least two weeks. The mixer initially experienced problems with liner fractures that were traced to combustion acoustics. A redesigned liner with heavier fasteners extended liner life significantly, but it is replaced on a scheduled basis.[303]

After a four-year shakedown and calibration process, the modified tunnel, with "Structures" dropped from its name, went into service in 1994, testing a hydrogen-fueled NASP concept demonstrator engine. While interest in hypersonic flight has ebbed and flowed over the years—NASP was canceled in 1995—NASA has continued scramjet development with a series of uncrewed experimental aircraft in its Hyper-X Program. Each flight of these planes represents the culmination of thousands of man-hours and hundreds of test hours, many of them in the 8-Foot HTT. The most recent of these is the X-43A, which set a world record for air-breathing vehicles of Mach 9.68 on 16 November 2004. The 8-Foot HTT was large enough to test a full-scale model of the X-43A.[304]

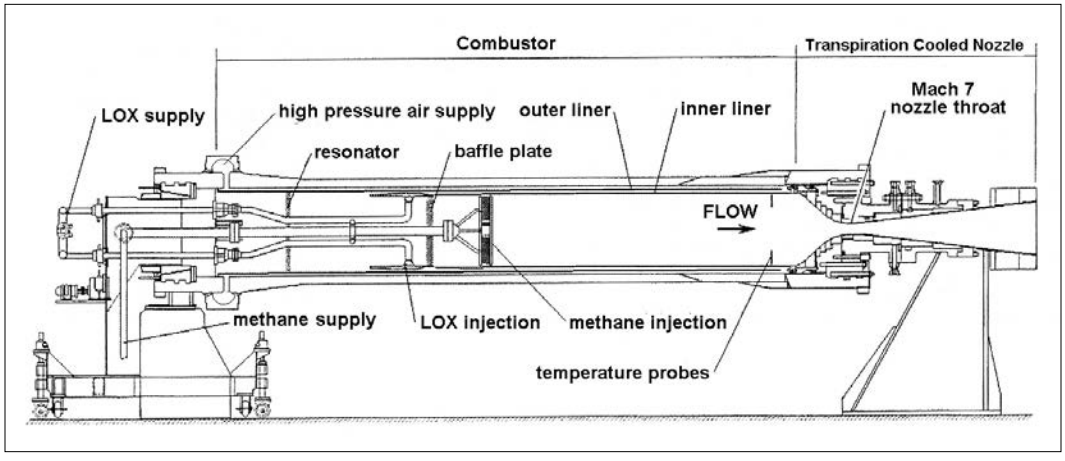
Work on hypersonic propulsion continues, though largely out of the public's eye, and the 8-Foot HTT, now equipped to test at three Mach numbers, is receiving additional modifications that will allow it to handle models burning more conventional hydrocarbon fuels instead of hydrogen. Similarly, development work on high-temperature materials continues, also without much publicity. Other facilities at Langley perform most of the early development work using small models or samples, but the 8-Foot HTT remains in service as the premier facility for large-scale testing in both fields.



A full-scale model of the X-43A scramjet vehicle during a powered test at Mach 7 in the 8-Foot High-Temperature Tunnel. Copper is used to aid internal cooling, and the model is inverted to expose the engine to an airstream unaffected by the support strut. On 16 November 2004, an X-43A reached Mach 9.68 in free flight, setting a record for air-breathing aircraft. (Photo credit: NASA LRC-2008-B701_P-00413)

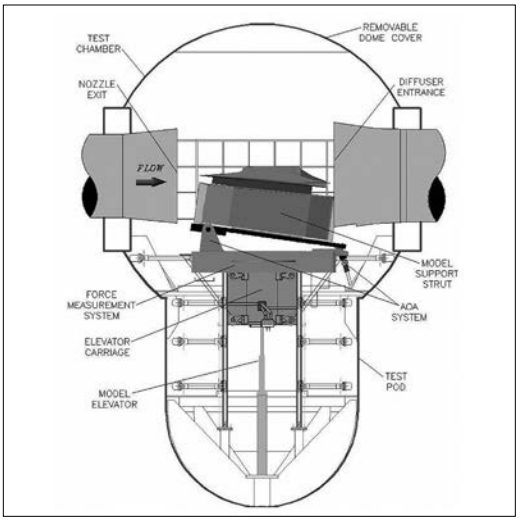


This labeled aerial view of the 8-Foot High-Temperature Tunnel from 1991 shows the entire complex. Note the separate storage areas needed for compressed air, liquid oxygen, and the different fuels. An elaborate lockout system ensures that incompatible fluids cannot be accidentally combined. (Photo credit: NASA LRC-1991-B701_P-05980)

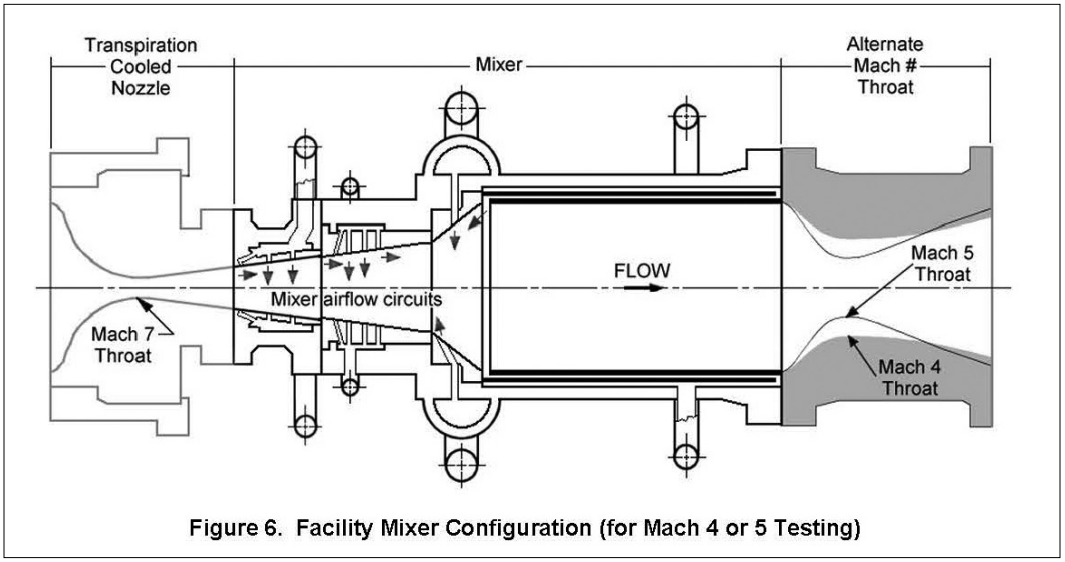


This drawing of the combustor identifies its major components. Air entering through the outer and inner liners cools the walls, and the liquid-oxygen injection system ensures that the vitiated-air test gas has the correct oxygen content for the test engine. (Image credit: AIAA 96-2197, Fig. 3)

The throat and first expansion section of the 8-Foot High-Temperature Tunnel's nozzle, seen here in 1993, was constructed of laminated copper plates. Hundreds of minute passages formed by channels etched into the plates conduct compressed air to the nozzle's inner surface. This air flowing into the gas stream protects the nozzle from extreme heat through a process known as transpiration. (Photo credit: NASA LRC-1993-B701_P-08102)



The major components of the 8-Foot High-Temperature Tunnel's test chamber are labeled in this drawing. The pod houses and protects the model elevator, shown here with a scramjet model raised into its test position and the umbilical wires and hoses that serve the model. (Image credit: NASA Document 20070003589, Fig. 7)



A mixer and alternate nozzles were added in 1996. When used, they replace most of the Mach 7 nozzle's expansion section. (Image credit: NASA Document 20070003589, Fig. 6)

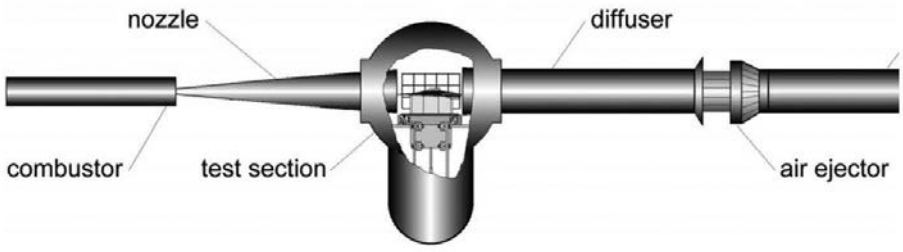
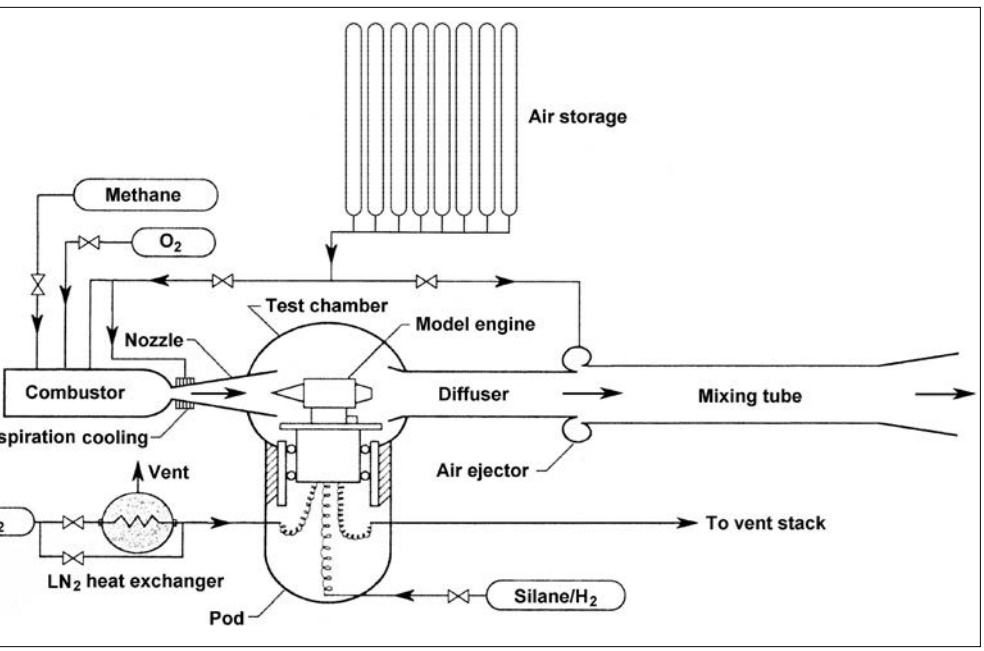


Figure 5. Facility Schematic

This drawing shows the 8-Foot High-Temperature Structures Tunnel as originally built. High-pressure air entered at the right end of the combustor (burner). The test chamber was 26 feet in diameter. Pressure within the test section was controlled by the air ejector, located outside the building, which reduced both the test section static pressure and the exhaust temperature. Only materials testing was done with the tunnel in this configuration. During the 1959–65 period, this tunnel was rebuilt into the 8-Foot High-Temperature Tunnel. (Image credit: NASA Document 20070003589, Fig. 5)



This schematic drawing shows the fuel systems added to convert the 8-Foot High-Temperature Structures Tunnel into the 8-Foot High-Temperature Tunnel for scramjet testing. (Image credit: AIAA 96-2197, Fig. 2)

2-FOOT HYPERSONIC TUNNEL

The 2-Foot Hypersonic Tunnel, seen here in 1992, was located on the top floor of the 8-Foot Transonic Pressure Tunnel's equipment building, directly above the TPT's control room. (Photo credit: NASA LRC-1992-B701-P-08848)

SIGNIFICANCE

The 2-Foot Hypersonic Tunnel (2-Foot HYST) was a two-dimensional hypersonic tunnel that used an air-ejector system to both drive the tunnel and produce very low static pressures in the test section to simulate high altitudes. It was primarily used for studies involving space launch vehicles in the upper atmosphere and atmospheric reentry vehicles.

DESCRIPTION

The 2-Foot HYST, also known as the 2-Foot High Supersonic Tunnel and the 2-Foot Hypersonic Facility, was installed on the top floor of the Equipment Building of the 8-Foot Transonic Pressure Tunnel (TPT), directly above the TPT's Control Room. This unusual location was selected to place the 2-Foot HST in close proximity to the high-volume compressed-air system already in place to serve the TPT. No portion of the 2-Foot HST was visible from outside the building (Building 640 in Langley's East Area).

The 2-Foot HYST was a two-dimensional, ejector-type tunnel that consisted of a hypersonic nozzle, test section, supersonic diffuser, and ejector mounted inside a larger duct. All of these components were 24 inches wide. A 1-foot-square sliding duct

penetrated the larger, outer duct and delivered air to the nozzle throat, which then expanded in 8.5 feet into the 2- by 2-foot test section. The nozzle's proportions and contour were optimized for Mach 6, but the throat was mounted on a wedge-and-jackscrew mechanism that allowed the throat opening to be varied from 0.10 to 6.75 inches. The sliding duct moved to accommodate nozzle adjustment. The nozzle adjustment enabled smooth start-up of the tunnel and an operating range between Mach 3 and 7. A sting mounted on an arc-shaped, vertical strut located the model at the center of the 4-foot, 6-inch-long test section. The 9-foot-long supersonic diffuser consisted of two contoured blocks. Fixed in place by flex plates at the end of the test section, they were mounted on jackscrews near the tip to permit the height of the tip opening to be adjusted from 3 to 20 inches.[305]

The diffuser formed the inner wall of the ejector nozzle. This ejector, which used air flowing through the larger duct and slots above and below the diffuser tip, induced a partial vacuum at the diffuser's tip. As with the diffuser, the ejector consisted of adjustable top and bottom contoured plates with a flexible inner liner. Their upstream ends were mounted on jackscrews, while their liners joined the subsonic diffuser immediately downstream. The two sets of jackscrews for the diffuser and ejector were driven by separate servos, but they operated in synch to maintain the size of the ejector slots throughout the range of the diffuser's motion. The ejector also included an adjustable second minimum 3 feet, 9.5 inches downstream from the diffuser tip, but this feature was rarely used.[306]

The 2-Foot HYST was connected to the pressurization system originally installed as part of the TPT. This system could serve only one of these two tunnels at a time. For the 2-Foot HST, two 100,000-cubic-foot-per-minute axial-flow compressors operating in parallel supplied air to the tunnel's outer duct and ejector, and all flow exiting the tunnel returned to these compressors for recirculation. Thus, the 2-Foot HYST operated as a blowdown tunnel with a closed-circuit air system. Air returning from the tunnel passed through a water-cooled pre-cooler to increase the air's density and compressor efficiency. Approximately 95 percent of the two compressors' discharge passed through water-cooled after-coolers and back to the tunnel's ejector duct. Located on the ground floor of the Equipment Building, these components existed as part of the TPT. About 3,000 cubic feet per minute of this flow was diverted to flow through a desiccant dryer to maintain the low dewpoint required. Approximately 10,000 cubic feet per minute of the compressor's discharge was extracted by another compressor, which pumped it through a heater and into the tunnel's nozzle. The heater consisted of nichrome tubes heated by DC electricity from a motor-generator. This allowed temperature control up to 1,500°F, but the tunnel's materials limited practical operation to approximately 1,000°F.[307]

HISTORY

The 2-Foot Hypersonic Tunnel was a Langley facility that seems to have lived its life in obscurity. While a description was published shortly after it opened in 1961, few

published records specifically mentioning tests performed in the facility have been identified, so little of its service history is now known.

Langley Real Property Office records for Building 640 indicate that engineering and construction for the 2-Foot HST began in 1958, and facility inventories show that the tunnel opened in 1961. Its initial cost is listed as $230,000. Interestingly, the facility inventories show the tunnel as occupying both Buildings 640 and 641, the latter being the 8-Foot High-Speed Tunnel (8-Foot HST), but no components associated with the 2-Foot HYST were ever located in Building 641, and the boundary-layer-removal system for the TPT that connected it to the 8-Foot HST was not installed until 1984, several years after the 2-Foot HYST was deactivated.[308]

The 2-Foot HYST grew out of a need to test an ultra-high-speed variant of the X-15 rocket-powered research airplane. The X-15A-2 was modified with two external fuel tanks that allowed longer burn times and, thus, higher speeds than the original design, but the performance of X-15A-2 with these tanks during flight and immediately after their jettisoning had to be verified by tests at speeds of up to Mach 6 before the modified configuration could fly. George M. Stokes, an engineer on the TPT's staff, conceived of using the TPT's massive compressors to power a small tunnel. Stokes determined that the maximum test section size for such a Mach 6 tunnel was 2 feet, which was small, but large enough to perform the tests. He also realized that the tunnel would be useful for tests involving missiles and launch vehicles, since many of them jettisoned expended stages at similar Mach numbers.[309]

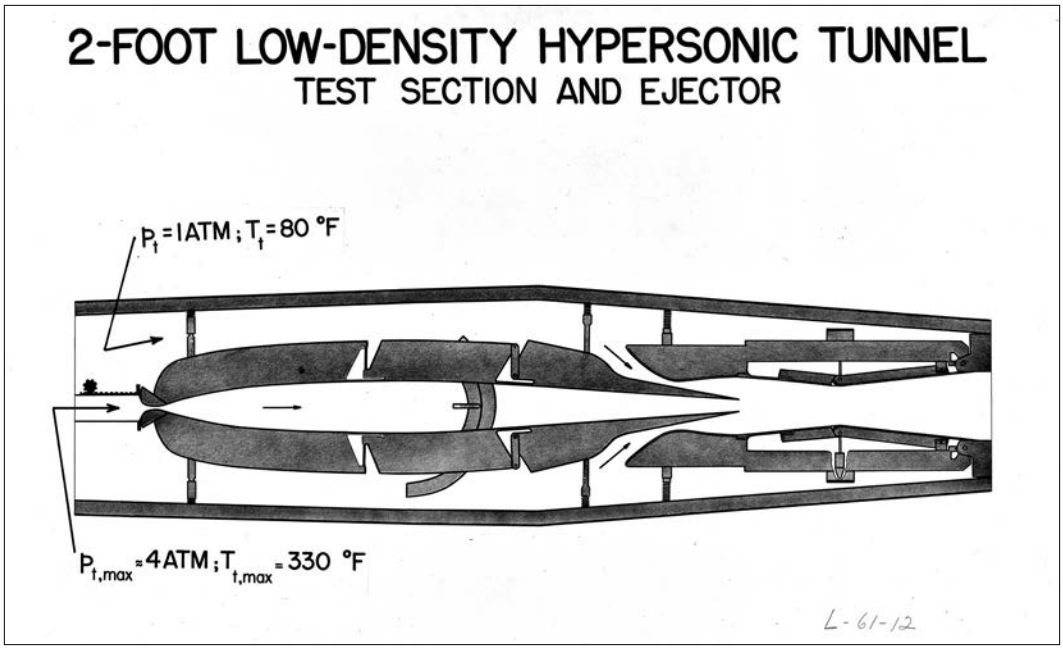
Management accepted Stokes's concept for the tunnel and approved funding for the 2-Foot HYST in 1958. Design and construction began immediately, and the facility opened in 1961. P. Kenneth Pierpont, a researcher on the TPT's staff, calibrated the tunnel and initiated its operation. Pierpont managed the 2-Foot HYST, but he and it remained a part of the Eight-Foot Tunnel Branch. While the test section measured 2 feet in diameter, the usable test volume was defined by the nose shock off the model and its reflection off the boundary layer along the tunnel's wall. Thus, as in all hypersonic tunnels, it was considerably smaller than the test section dimensions. This volume was a "body" of revolution that, when viewed from any side, took the shape of a rhombus. Models were built to fit within this volume.[310]

One interesting test program in the 2-Foot HYST investigated the potential of flexible-canopy, rigid-frame paragliders—sometimes known as Rogallo wings after their inventor, Francis Rogallo—as recovery devices for expended rocket boosters and spacecraft reentering the atmosphere. To be useful, the device had to be stable and inherently turn into the wind regardless of its initial deployment attitude. Since deployment would occur at a high altitude and speed, researchers selected the 2-Foot HYST for the tests. These tests revealed generally good performance, except for one case that doomed the paraglider from actual use—its flexible wings would not extend when it was deployed facing backward.[311]

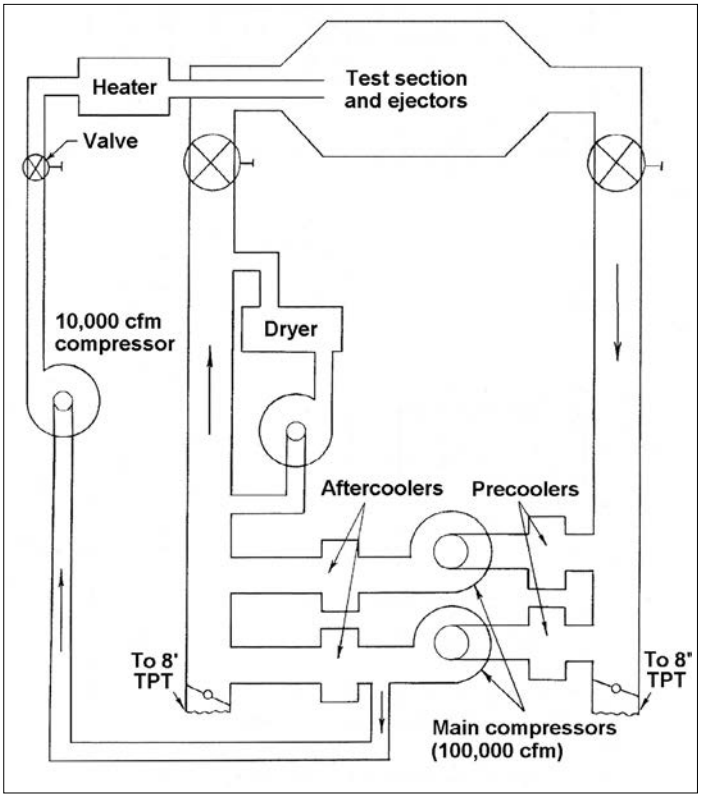
The 2-Foot HYST also made a little-known, but vital, contribution to the Apollo/Saturn V program. Using a small model of the stack and high-pressure nitrogen gas to simulate the rocket plume, schlieren photographs revealed that the ionized plume would cause a loss of radio signals from the vehicle for a longer time during staging than anticipated. The difference was great enough that it would likely result in the mission being aborted. Additional testing confirmed this only days before the Saturn V's first scheduled test flight. Engineers at Marshall Space Flight Center were able to modify the control software to accept a longer loss of signal, and the flight (Apollo 4, 9 November 1967) was a complete success.[312]

The 2-Foot HYST operated until about 1971, at which time it was dismantled and replaced with a pilot model for the 0.3-Meter Transonic Cryogenic Tunnel. Portions of the TPT and 2-Foot HYST's air system were used to power the new tunnel. The pilot tunnel was deactivated after the 0.3-Meter Transonic Cryogenic Tunnel opened in 1973. NASA demolished the TPT, including the pilot tunnel, in 2011.[313]

A flexible-canopy paraglider mounted in the 2-Foot Hypersonic Tunnel in 1962 for tests to determine its suitability as a recovery device for spacecraft and expended rocket boosters. These tests simulated high-altitude atmospheric deployment at Mach 4.5 in a wide variety of attitudes. (Photo credit: NASA LRC-1962-B701_P-03267)

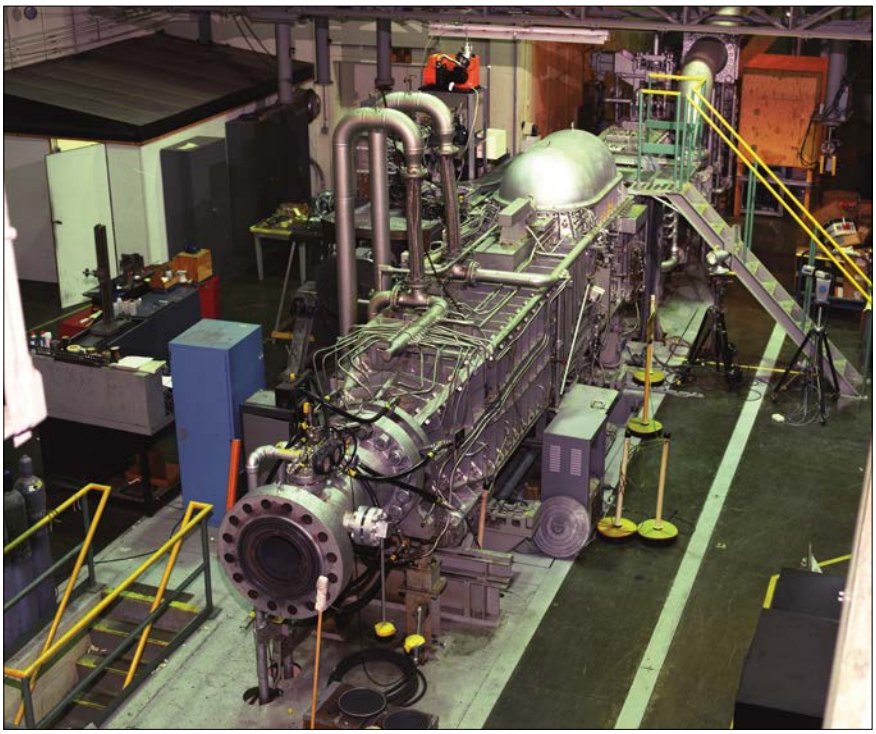


This section drawing of the core of the 2-Foot Hypersonic Tunnel shows its major components. Note how the tunnel used an ejector at the end of the diffuser to help induce flow through the nozzle and maintain a low pressure in the test section. The dashed rhombus defines the useful test volume. At the right tip of the rhombus is the sting and arc for pitch adjustment. The station numbers are in inches. (Image credit: NASA LRC-1961-B701_P-00012)



This schematic diagram shows how the 2-Foot Hypersonic Tunnel (at top) made use of the large air compressors already in place at the 8-Foot Transonic Pressure Tunnel. (Image credit: NASA TN D-939, Fig. 2)

31-INCH MACH 10 TUNNEL



The 31-Inch Mach 10 Tunnel top wall, flow field survey probe, and mounting flange in Building 1251-A in 1996. (Photo credit: NASA LRC-1996-B701_P-01920)

SIGNIFICANCE

The 31-Inch Mach 10 Tunnel (31-Inch M10), originally named the Continuous-Flow Hypersonic Tunnel (CFHT), was the first large hypersonic tunnel capable of continuous operation. Hosting a wide range of aerodynamic and heat-transfer tests, it remains one of NASA's most active hypersonic tunnels.

DESCRIPTION

The 31-Inch M10 is located in Building 1251-A, which is contiguous with Building 1251, which houses Langley's Unitary Plan Wind Tunnel. The project to build this tunnel, known originally as the CFHT, began before the Unitary Plan Tunnel was complete, so it was an easy matter to finish a space in Building 1251 for the CFHT, yet identify it with a separate number for managerial purposes. The main portion of the CFHT, including its control valves, settling chamber, nozzle, test section, diffuser, and compressors, is inside the building, but the high-pressure air storage bottles, heater, and vacuum sphere are outside. The tunnel's centerline is approximately 5.5 feet above the floor. The compressors and control panels occupy separate rooms adjacent to the tunnel. Most of the air system piping is exposed to facilitate inspection and maintenance.[314]

Designed to operate under pressures as high as 2,000 psi, the water-cooled nozzle, 31- by 31-inch test section, and diffuser are constructed from heavy steel plate with vertical and horizontal ribs for added strength and stiffness. The air storage bottles and vacuum sphere are also fabricated from steel, and the steel piping has bolted flange joints. The test section includes a model-injection device that operates horizontally, though this somewhat reduces the access for flow visualization equipment. Nevertheless, surface oil-flow and schlieren photography techniques are possible. The instrumentation also includes a six-component, strain-gage balance and devices for heat-transfer studies, including thin-film heat-transfer gages and phosphor-thermography cameras.

HISTORY

The concept for what became the CFHT emerged during the last two years of the NACA's existence, but it entered service as a NASA facility. A continuous-flow hypersonic facility had been on the mind of Langley engineer Eugene Love since the mid-1950s. At that time, the NACA's hypersonic tunnels—all of them "conventional," the accepted term for hypersonic blowdown tunnels—could produce acceptable speeds for useful research, but their short run times, typically less than 2 minutes for a half hour of pumping time, and general inflexibility in how models could be mounted and inserted into the air flow left Love and other researchers wanting more.[315]

Accumulating the ideas of others and merging them with his, Love envisioned a Mach 12 tunnel with a test section around 2.5 feet in size. The tunnel itself would be a conventional blowdown tunnel, but its air supply and vacuum exhaust system would be considerably larger to obtain the longest run times possible. In fact, what Love really wanted was a continuous-flow tunnel.

Love's team started by designing the tunnel and its basic air system, selecting a three-dimensional square nozzle expanding into a 31- by 31-inch test section equipped with a model-injection device. To prevent air liquefaction, they specified a 13-megawatt electric heater to preheat the test air to the desired temperature, typically about 1,450°F, before each run and to maintain that temperature throughout the test. This temperature into the nozzle required that it be water-cooled to prevent distortion and damage. Additional cooling was needed in the diffuser, where decelerating air rapidly became hotter as its kinetic energy transformed into thermal energy. An aftercooler pulled the temperature down to approximately 100°F to maximize the efficiency of the vacuum sphere. Though having a greater capacity than the equipment supporting most of Langley's other hypersonic tunnels, the blowdown portion of this air system introduced nothing new.[316]

A continuous-flow hypersonic tunnel, if it could be done, would, however, be quite new. With the tunnel design set, Love's engineers tackled the compressor problem. The calculated pressure ratio of 700:1 across the nozzle and test section was far beyond what a single axial-flow compressor could produce mounted directly in a tunnel circuit.

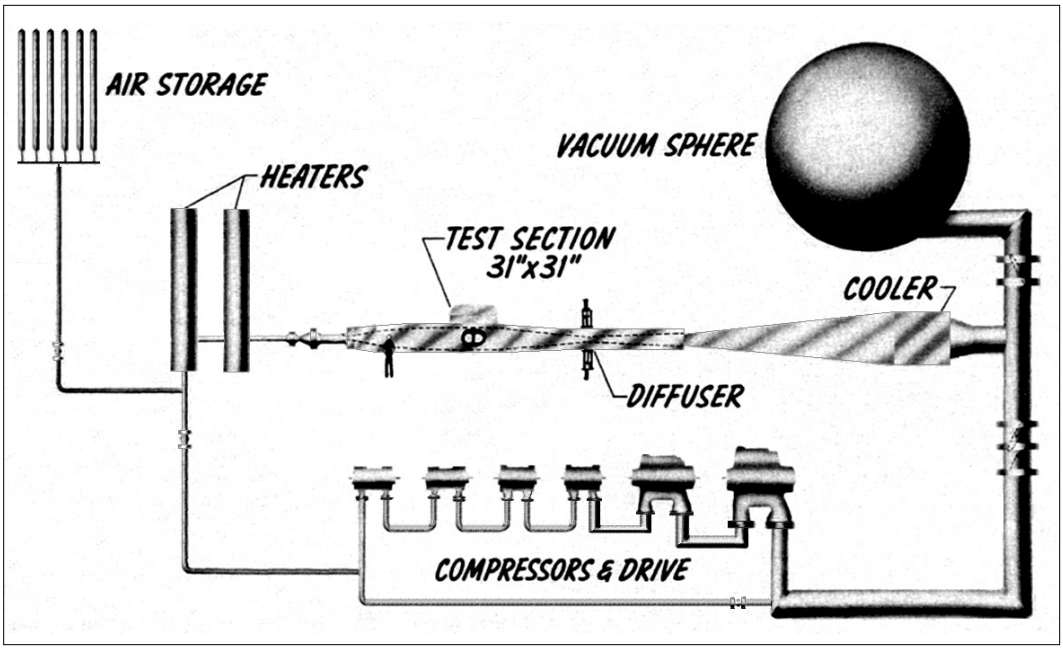
Multiple compressors connected in series would be necessary, and the team designed a set of six. The first two of the series were designed to handle large volumes of relatively low-density air. The last four would compress that air in stages that were sufficient for filling the air storage bottles or passing directly through the tunnel. The six-compressor concept looked good on paper, but the sixth compressor did not perform in a stable manner at startup. The team had no choice but to remove it from the circuit. The five remaining stages were adequate only for Mach 10, and a nozzle was designed and built for that speed.

In 1962, the CFHT began shakedown and calibration runs as a conventional blow-down tunnel, and it entered service the following year. The start-up difficulties with the compressor system took another year to resolve, but the tunnel finally achieved continuous-flow operation in 1964.[317]

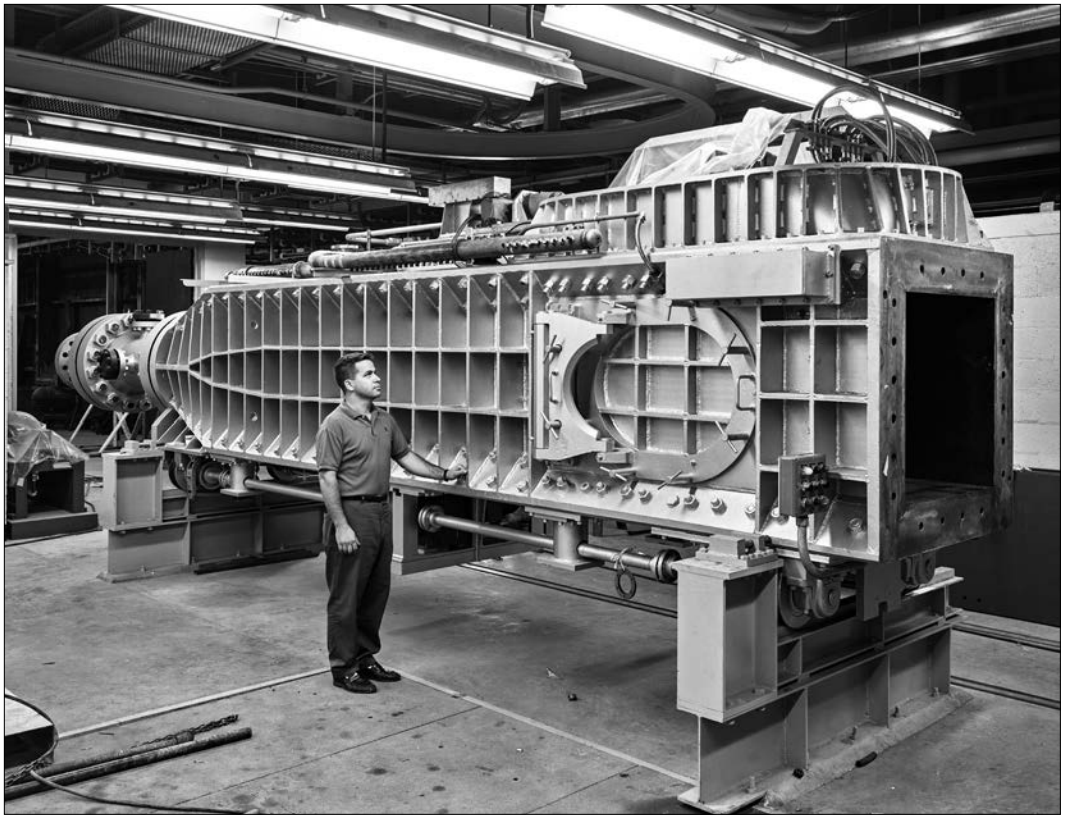
The CFHT proved to be a very capable and useful facility, and it was soon well booked with a wide range of research projects. Not surprisingly, many of these involved spacecraft and atmospheric entry, but the nation's various forays into hypersonic aircraft also generated major test programs. As discussed in the 15-Inch High-Temperature Tunnel and Hypersonic Facilities Complex chapters, the CFHT is one of several tunnels whose data are compared to validate data in situations where real-gas effects predominate. Other programs in the CFHT investigate topics from general aerodynamic interest to tests of very specific details of particular vehicles. Vehicles tested range from lifting bodies, such as the HL-20 and X-34, to the Space Shuttle orbiter, and, recently, NASA's Orion Crew Exploration Vehicle.[318]

In operation, the continuous-flow capability proved to be both expensive and unneeded, and it was rarely used after about 1976. Improvements in test design and instrumentation, along with the tunnel's low turbulence, produced high-quality data from short runs—typically between 1 and 2 minutes—and reduced power consumption considerably. By the 1990s, Langley had changed the facility's name to the 31-Inch Mach 10 Tunnel, and recent publications by the Aerodynamics, Aerothermodynamics and Acoustics Competency at Langley indicate a 120-second maximum run time.[319]

As one of NASA's premier hypersonic facilities, the 31-Inch Mach 10 Tunnel has received numerous enhancements in instrumentation and data-acquisition capability over the years. It remains in service.



This simplified schematic diagram shows the 31-Inch Mach 10 Tunnel's major components. The compressors can be used to evacuate the sphere and charge the air bottles for blowdown operations, or run in a closed-loop, continuous-flow mode. This early diagram shows the six compressors originally planned. Only five ultimately proved to be practical. (Image credit: NASA TM X-1130 - M10)



This 1961 view shows the nozzle and test section of the 31-Inch Mach 10 Tunnel. Flow is left to right. (Photo credit: NASA LRC-1961-B701_P-06268)

(Top) Several configurations of the X-43A scramjet vehicle tested in the 31-Inch Mach 10 Tunnel, along with the Pegasus booster used to boost the craft to its operating altitude. (Bottom) One version mated to the Pegasus. Note the 6-inch scale in both of these 2000 views. The models were sting-mounted. (Photo credits: NASA LRC-2000-B701_P-01468 and NASA LRC-2000-B701_P-01472)

6-INCH EXPANSION TUBE HYPERSONIC PULSE FACILITY

Building 1200, seen here in 1991, was built to house the Hot Gas Radiation Facility and its 6-Inch Expansion Tube. It is currently occupied by the Advanced Technology Research Laboratory and contains no wind tunnels. (Photo credit: NASA LRC-1991-B701_P-03852)

SIGNIFICANCE

The 6-Inch Expansion Tube (6-Inch ET) was NASA's second expansion tube type of impulse tunnel and its first permanent one. After 15 years of service supporting planetary atmospheric entry studies at Langley, it was relocated to Ronkonkoma, New York, where it was operated as the Hypersonic Pulse Facility by General Applied Science Laboratories (GASL) in a joint venture with NASA.

DESCRIPTION

The 6-Inch ET originally built at Langley was a 235-foot-long steel pipe with enlarged cylinders at each end. One end included a driver chamber and intermediate chamber, separated by a high-pressure diaphragm. An extension to the driver formed a collector, where cables from a 10-megajoule capacitor bank terminated at four collector rings. A cylindrical test section-dump tank formed the opposite end. Between the two ends was a 6-inch-diameter pipe consisting of 10 flanged sections and totaling 166 feet long. Steel bents supported the tube with its centerline approximately 3 feet above the floor of a long room in Building 1200, which was built for it in Langley's West Area. The tube's driver and intermediate chambers, along with its capacitor bank, extended into a separate room.[320]

The 6-Inch ET was largely a scaled-up version of the Pilot Model Expansion Tube (PMET), but some of its proportions were different, reflecting the different gas volumes involved and lessons learned in the PMET. While the expansion chamber's diameter increased 60 percent, its length was 2.3 times longer than its predecessor. The engineers reduced the lengths of the driver and intermediate chambers to 8 feet each from the PMET's 14 and 24 feet. The increased size required greater driver arc power, and the engineers installed a 10-megajoule capacitor bank, four times that of the PMET.[321]

To improve flow quality, researchers could use a double diaphragm in the high-pressure (first) location between the driver and intermediate chambers. Polyethylene terephthalate (DuPont trade name Mylar) became the primary material for the second diaphragm.[322]

After its move to GASL, the 6-Inch ET became known as the Hypersonic Pulse Facility, or simply HYPULSE. Its basic arrangement is similar to that at Langley, but it was reerected with a shorter expansion tube, reducing its overall length to 115 feet. This arrangement worked well for speeds in the Mach 12–25 range, but the need to test at slower speeds led GASL to build alternates for most of the major components that could be assembled in any of several configurations. These permitted operation at Mach numbers as low as 5.

Additionally, GASL developed a combustion driver that can substitute for the electric-arc driver, and, for safety reasons, the laboratory now uses helium instead of hydrogen as the driver gas, even though helium requires operation at 10 times the initial pressure of hydrogen. As at Langley, the intermediate chamber can be charged with any desired test gas.[323]

HISTORY

The success of the PMET in 1963 quickly generated interest in building a larger, permanent expansion tube able to accommodate larger models. Robert Trimpi and the PMET team began to design what was to become the 6-Inch Expansion Tube and received funding to build it, along with a new structure to house the tube and associated shop and offices, the next year. Langley named the new building the Hot Gas Radiation Facility, reflecting its primary mission of investigating radiative heat transfer around bodies entering planetary atmospheres, and the name was sometimes applied to the 6-Inch ET as well.

Although the expansion-tube concept had been validated with the PMET, the new 6-Inch ET required the same degree of detailed engineering as its predecessor. Because of the non-linear changes in such things as boundary-layer growth as gases accelerate, the design involved more than a simple, proportional enlargement of the PMET. While the resulting 6-Inch ET looked much like an enlarged PMET, the length-to-diameter ratios of its various chambers were slightly different. The two biggest physical changes were in the intermediate chamber, which was shortened by 6 feet, and the fourfold increase in capacitor power.[324]

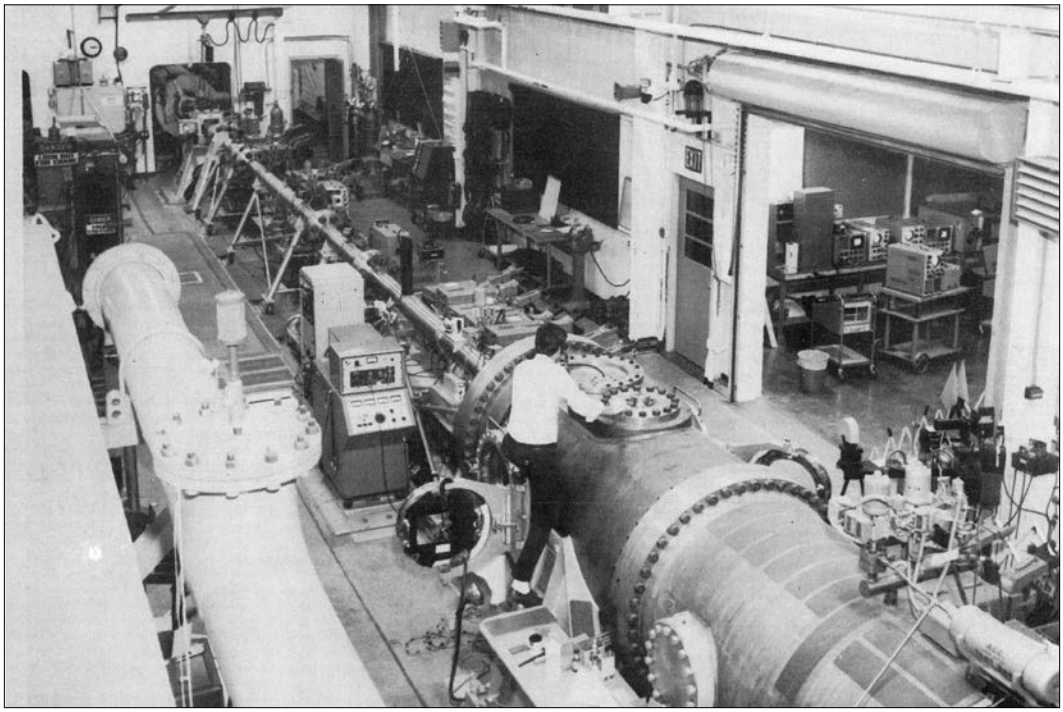
The 6-Inch ET entered service in 1967. With the proven performance of "blunt bodies" for atmospheric entry during the decade following the concept's development by H. Julian "Harvey" Allen of the NACA's Ames Laboratory—NASA's Ames Research Center after 1958—it is not surprising to find that most of the 6-Inch ET's early test programs involved variations on the concept. With the Apollo lunar missions still two years in the future, no spacecraft had yet experienced a 25,000-mile-per-hour atmospheric entry. Apollo's design had been finalized by 1966, but the 6-Inch ET tests confirmed the design in the most realistic, albeit brief, tests possible. With the human spaceflight program in high gear and additional space exploration planned in the near future, other programs began to study entries into the atmospheres of other planets, particularly Mars and Venus.[325]

These crewed interplanetary missions were not to be. Despite sporadic projects, NASA's research interests had largely shifted away from hypersonic flight by the early 1980s, and the agency looked at eliminating some of its less-lucrative facilities as a partial response to budgetary restraints. GASL, a commercial organization that performed aerodynamic testing for the United States military and its suppliers, negotiated an arrangement with NASA whereby the 6-Inch ET would be moved to GASL's facility in Ronkonkoma, New York. GASL would reerect and operate the tube as part of its suite of wind tunnels. It would remain a NASA facility, but GASL would be able to contract with others for test work. The move occurred in 1983, but with a dearth of hypersonic work at the time, GASL was slow to reerect the tube.

In 1986, President Ronald Reagan's proposal for what became known as the National Aero-Space Plane (NASP) revived interest in hypersonic flight, and GASL decided the time had come to make the 6-Inch ET, which they renamed the Hypersonic Pulse Facility, or HYPULSE, operational. HYPULSE entered service for GASL in 1989, but in an arrangement somewhat modified from that at Langley, primarily because the NASP's flight regime would not extend past about Mach 20, making the tube's former Mach 30 capability unnecessary. Reerected with a shortened expansion tube, HYPULSE was, at 115 feet, slightly less than half the overall length of the 6-Inch ET.[326]

Since entering service as HYPULSE, GASL has developed additional modifications for the facility that allow it to operate in two different modes and speed ranges. It can be configured as a reflected-shock tube for the Mach 5–10 range or as a shock-expansion tube for Mach 12–25. NASA's Hyper-X Program to build and fly small, uncrewed scramjet test aircraft up to about Mach 10 included testing in HYPULSE during the late 1990s and early 2000s. To support this, GASL installed the capability to furnish fuel to model engines, using Ludwieg tubes to deliver bursts of fuel during the brief runs. GASL also has developed advanced instrumentation and measurement systems for the facility, including rapid-response, thin-film thermocouple gages, multiframe high-speed schlieren imaging, and laser holographic interferometry, a technique for imaging the flow field around the model.[327]

The HYPULSE Facility, rebuilt and updated, is in service at the Hypersonics and Applied Research Facility at Purdue University. Refurbishment of Langley's Building 1200 for other uses removed all evidence of the 6-Inch Expansion Tube's tenure there.



This view shows the 6-Inch Expansion Tube in Building 1200 in 1974. The technician is standing next to the test section. The driver extends into a room in the background. (Photo credit: NASA LRC-1974-B701-00382)

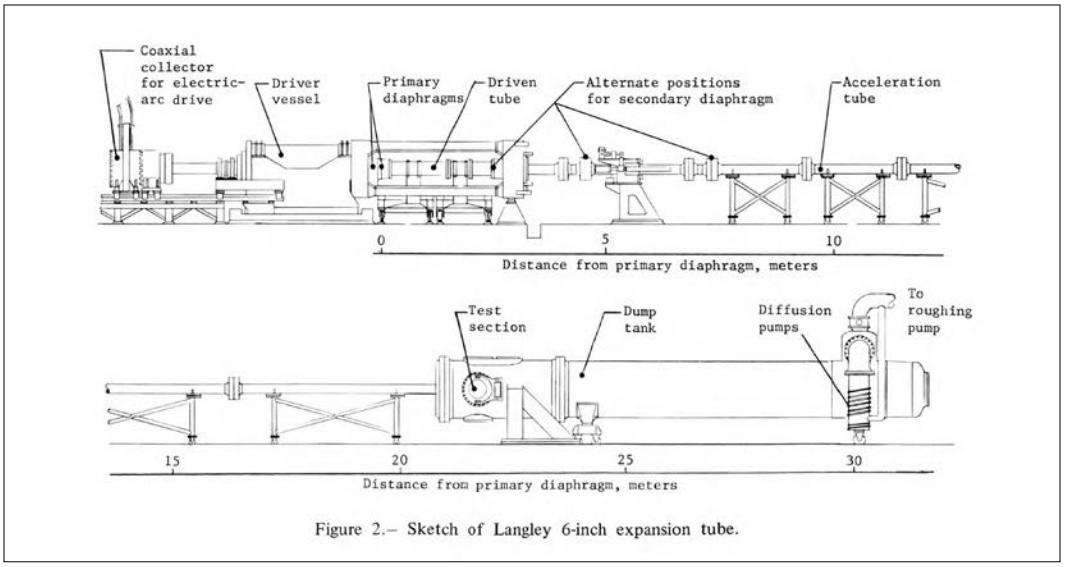
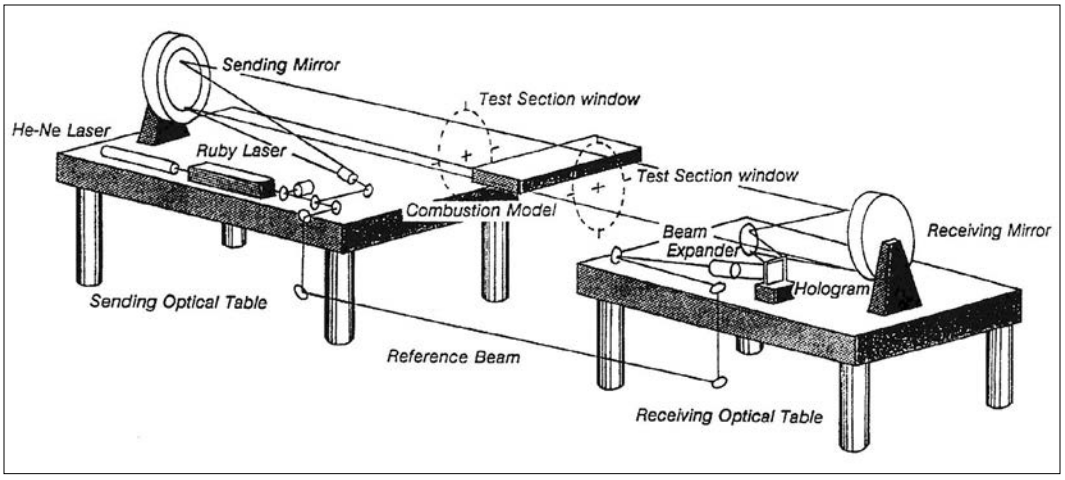
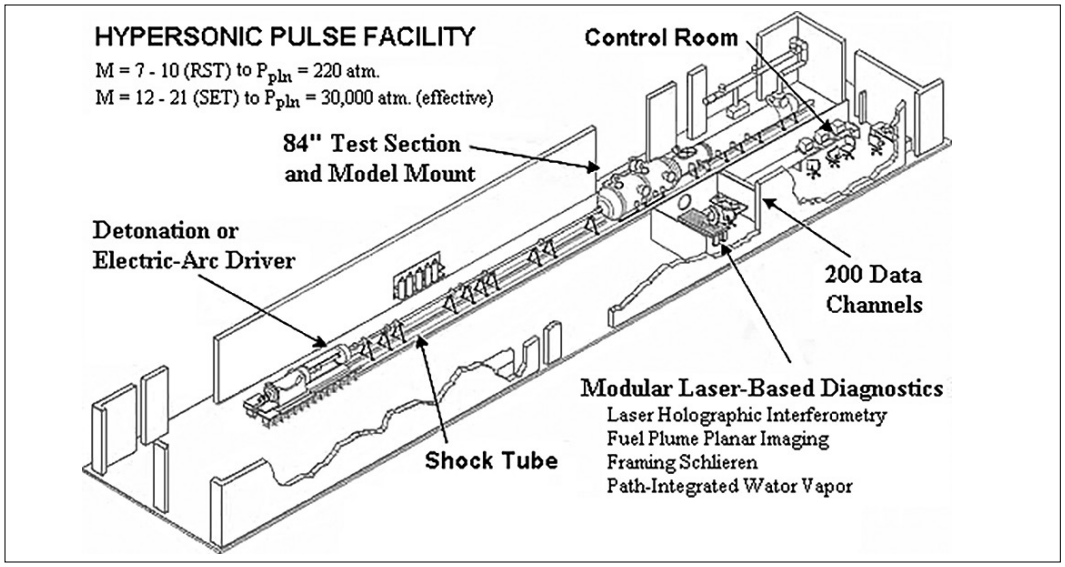


Figure 2.– Sketch of Langley 6-inch expansion tube.

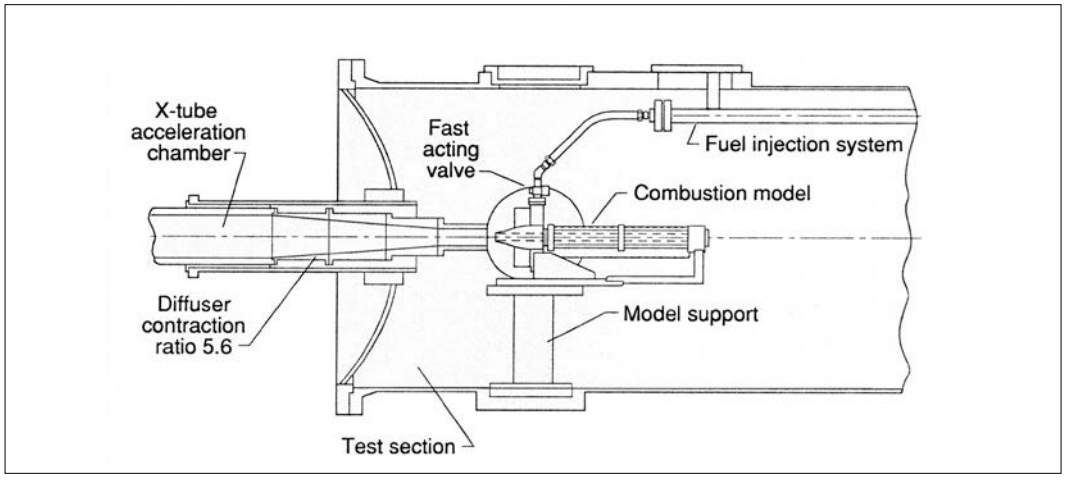
This drawing shows the major components and basic dimensions of the 6-Inch Expansion Tube as installed in the Hot Gas Radiation Facility, Building 1200, at Langley. The expansion chamber, here shown with a break, consisted of 10 sections of pipe. (Image credit: NASA TM X-3240, Fig. 2)



As this drawing shows, the 6-Inch Expansion Tube's test section occupied the inlet portion of the dump tank. (Image credit: NASA CR-191578, Fig. 4)



This pictorial drawing shows the general arrangement of the Hypersonic Pulse Facility during its service at General Applied Science Laboratories' Ronkonkoma, New York, facility. Though similar to its arrangement as the 6-Inch Expansion Tube, the device underwent numerous modifications after its move from Langley in 1983. While managed by General Applied Science Laboratories (GASL), HYPULSE was still considered a NASA facility. GASL eventually became part of Northrop Grumman, and Northrop donated the facility to the Hypersonics and Applied Research Facility (HARF) at Purdue University in West Lafayette, Indiana, in 2020. (Image credit: AIAA-2001-324, Fig. 1)



This diagram shows the laser holographic interferometer (LHI) system used in the Hypersonic Pulse Facility. The LHI system uses light of different wavelengths from two lasers to generate a three-dimensional image of the flow field around a model in the test section. It is commonly used during scramjet tests. (Image credit: NASA CR-191578, Fig. 4)

14- BY 22-FOOT SUBSONIC TUNNEL

In this 1999 aerial view, the 14- by 22-Foot Tunnel dwarfs the 7- by 10-Foot High-Speed Tunnel at the upper left. Note the three concrete pedestals needed to support the circular fan and motor section and the separate air exhaust and intake towers. The 7- by 10-Foot High-Speed Tunnel was demolished five years later. (Photo credit: NASA LRC-1999-B701_P-02337)

SIGNIFICANCE

The 14- by 22-Foot Subsonic Tunnel, also known at various times as the 14- by 22-Foot V/STOL Transition Tunnel, the 4- by 7-Meter Tunnel, and simply the 14- by 22-Foot Tunnel, represents one of NASA's largest investments in low-speed flight. Thus, this tunnel is significant in marking a departure from massive investments in facilities to research supersonic, hypersonic, and hypervelocity flight to investments that promised greater utilization in the study of flight regimes encountered by virtually all types of aircraft. While this tunnel is in many ways a descendant of the 17-foot test section installed in the 7- by 10-Foot Low-Speed Tunnel, the opportunity to construct a totally new facility allowed NASA engineers to incorporate several features that continue to make the tunnel practical, flexible, and economical. Chief among these are the ability to operate with the test section open or closed, a large moving ground plane, and the use of several interchangeable model support carts. While not unique to the 14- by 22-Foot Subsonic Tunnel, these model support carts were unprecedented in their size and flexibility.

DESCRIPTION

The 14- by 22-Foot Subsonic Tunnel is a large, atmospheric wind tunnel utilizing externally braced steel-shell construction. Its single circuit has a rectangular cross section,

except for transitions into a circular fan section in the long return leg, and it features mitered corners with turning vanes. An air exhaust tower extends above the tunnel just ahead of the third corner, and an intake tower is about 60 feet downstream from the test section. As with other atmospheric tunnels, this air-exchange system, divided here instead of combined into a single tower, exchanges a small portion of the air inside the tunnel with atmospheric air to remove heat generated by the drive motor and fan. The facility is on the south side of Building 1212 and is listed as Building 1212-C. Building 1212-A, the 7- by 10-Foot Low-Speed Wind Tunnel this tunnel replaced, was ultimately demolished as modifications to this facility needed that space.

Overall, the tunnel measures approximately 360 feet by 125 feet at its greatest extent, and it reaches a maximum of 62 feet high over its exhaust tower. The test section is surrounded by a cubical, steel-framed chamber 77 feet wide by 82 feet long by 61.6 feet high. The exterior is painted white to minimize the absorption of solar heat. Attached to the north side of the test chamber is a two-story structure about 100 feet by 125 feet in size that houses the model preparation areas and data acquisition center. This adjoins the offices in Building 1212.[328]

The test section is both large and flexible in how it can be configured for a variety of tests. In its closed mode, the test section measures 14.5 feet high, 21.75 feet wide, and 50 feet long. Its inlet nozzle has a 9:1 contraction ratio, and the sidewalls diverge at 0.1 degree to accommodate boundary layer growth. A boundary layer removal system, driven by a 900-horsepower blower, can extract up to 100,000 cubic feet of air per minute through a perforated plate in the floor at the beginning of the test section. This system is most often used during tests where ground effects are significant. Many of those tests also use the facility's moving-belt ground plane, which can simulate ground moving beneath a vehicle at up to 82 mph. The walls, ceiling, and floor are equipped with adjustable slots to minimize wall effects on models. The openings can be varied from 0 to over 10 percent. The tunnel's maximum speed in the closed mode is 230 mph. For tests needing an open test section, the sidewalls and ceiling can be raised to form an Eiffel-type chamber 24.5 feet high and 77 feet wide. For these tests, the 14- by 22-foot inlet nozzle retains its closed-section configuration, and a flow collector is erected at the test chamber's exit to enhance the recapture of air into the tunnel's diffuser. The maximum speed in this mode is limited to 184 mph. In either mode, the test section can be lined with fiberglass acoustic panels having a sound absorption coefficient of approximately 95 percent, a feature particularly useful in rotorcraft studies.[329]

The airflow is generated by a 9-blade, 40-foot-diameter fan driven by two electric motors housed in a nacelle in the long return leg. In common with many wind tunnels, the fan blades are laminated spruce, and they have protective fiberglass covers on their leading edges. For low-speed, low-dynamic-pressure tests, only the smaller, 1,350-horsepower, DC motor is energized. For tests requiring more power, a 6,650-horsepower AC motor is added. Both are variable-speed motors, and they turn a common shaft that is directly connected to the fan. A set of adjustable flow control vanes after corner 1

helps maintain stable, non-stratified airflow, especially at low speeds. Motor speed, along with all other test functions, is directed from a control room located in the east end of the test chamber. Control and data-acquisition functions are processed by computer hardware in an adjoining room.[330]

Perhaps the most innovative feature of the 14- by 22-Foot Subsonic Tunnel is its system of model support. Much of the instrumentation and mounting hardware are common designs, but different mounting arrangements were installed on large, but portable, carts that form much of the test section floor when in place. Four carts are available, each with specific mounting and balance equipment. Most tests use one of the sting mount configurations. The test section has two bays that enable combinations of these carts, along with supporting fixtures like the moving-belt ground plane cart or simply filler panels, to be installed. Depending on the cart used, angle of attack or angle of sideslip can be varied up to 50 degrees. These carts are fitted with connections to supply compressed air and electricity to powered models as well. To move these carts, compressed air is routed to air bearings that lift the cart just clear of the sealed concrete floor that makes up the lower level of the test section and model preparation areas. So elevated, the 40-ton carts are easily moved and precisely located. Hydraulic lifts raise them into position in the test section, where they are locked into place, forming part of the tunnel's floor. This portability feature also makes it possible to mount and statically test models in the model preparation area, or to demount them, while another test is being conducted in the tunnel.[331]

A two-component laser velocimetry system is available when detailed measurements of flow fields around a model are needed. This system uses an argon-ion laser to sense the local horizontal and vertical motion at thousands of points in space around the model. A computer then assembles these into any of several different presentations or databases. A laboratory adjacent to the test section allows the system to be prepared and calibrated while other tests are being conducted.[332]

Several flow visualization techniques can be employed, including tufts, smoke, and liquid crystal coatings, with some of these using ultraviolet lighting to enhance visibility. A complete data acquisition system is linked to strain gages on the sting and to various instruments on the model to record all test data. Virtually all data are now recorded digitally, and tests can be monitored and recorded via a closed-circuit television system.[333]

HISTORY

The 14- by 22-Foot Subsonic Tunnel, one of NASA's newer wind tunnels, was built to fill a growing need for facilities able to perform realistic testing in close proximity to the ground. At altitude, aircraft encounter largely homogeneous air; that is, the air reacts to the airplane moving through it essentially the same way in all directions. Close to the ground, as in takeoff and landing, and during the near-ground and hovering flight of helicopters and vertical/short takeoff and landing (V/STOL) craft, how the air interacts with the nearby ground has a significant effect on how that same air interacts with the

aircraft. Downwash is reflected in a turbulent manner, and this reflected flow impacts the vehicle. Though overshadowed in the public's eye by the so-called "space race" of the 1960s, interest in V/STOL craft flourished during this time, with intense interest in both military and commercial applications. The military helicopter matured during the Vietnam War, and commercial designers were searching for ways to handle the growing amount of short-range traffic, particularly the demand for aircraft able to operate economically out of small airfields close to city centers. Concepts that had been tried unsuccessfully in the 1950s, such as tilting rotors and jet engines, reemerged a decade later with improved hardware, and engineers came up with new ways to augment low-speed lift, too.

Adding the 17-foot test section to Langley's 7- by 10-Foot Low-Speed Wind Tunnel had demonstrated the value of a large, low-speed tunnel for such studies, but being an "add-on," it possessed a number of compromises and weaknesses. Other, more-modern tunnels had introduced devices and fixtures to improve tunnel productivity that could not be retrofitted into the existing tunnel. The 40- by 80-Foot Full-Scale Tunnel at NASA's Ames Research Center had begun testing full-sized, powered V/STOL vehicles, an expensive proposition, and NASA's Lewis (now Glenn) Research Center had followed Langley's lead by installing a 9- by 15-foot low-speed test section in its 8- by 6-Foot Supersonic Tunnel. Thus, the growing need for low-speed, low-altitude testing and the opportunity to incorporate a modern design and fixtures provided strong support for construction of a new wind tunnel tailored for these specialized tests. Langley engineers merged these ideas into what they initially termed the V/STOL Transition Research Wind Tunnel, and NASA succeeded in obtaining funds for it beginning in 1965. Construction began in earnest in 1966, and the facility opened in 1970.[334]

The tunnel's equipment and capabilities, described above, quickly attracted a large number of test programs involving not only V/STOL aircraft, but also just about everything from helicopters to supersonic, and even hypersonic, planes. Regardless of their ultimate speed and altitude capabilities, they all had to fly safely low and slow as well. As intended, the 14- by 22-Foot Subsonic Tunnel had equipment to host tests that could not be done easily—if at all—elsewhere. The modular model carts permitted, for example, a model to be sting-supported from one cart, but cantilevered over the adjacent moving-belt cart to reproduce takeoff and transition to low-altitude flight with accurate ground effects.

Like almost all large machines, this tunnel had its start-up problems, and the staff had to learn the best ways to use its novel features, like the adjustable slots, to get the best results. Kalman Grunwald built a ⅕-scale model of the test section in an open-circuit tunnel to test various slot configurations, using additional tests in the 7- by 10-Foot Low-Speed Tunnel as a control. That investigation led to slot arrangements that substantially reduced wall effects in the new tunnel, nearly eliminating them in some cases.[335]

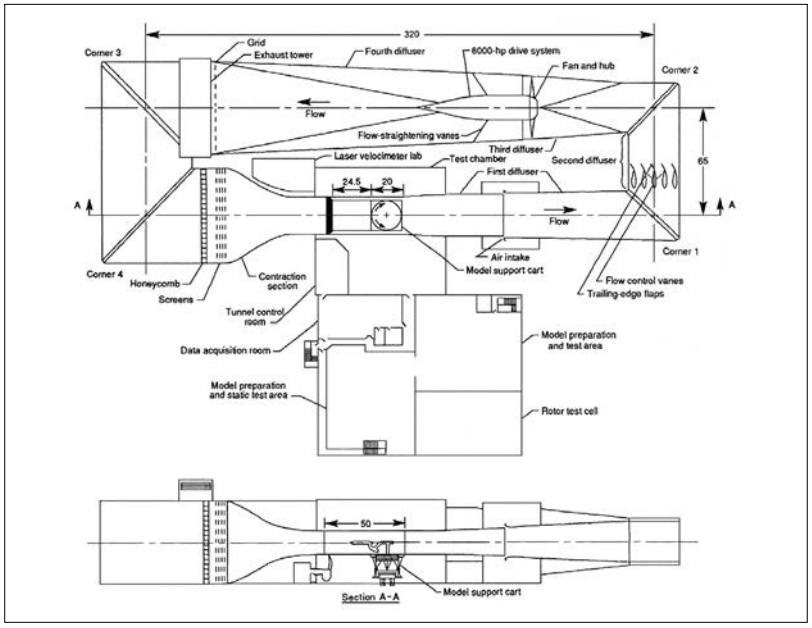
Initially, the air flow was not as stable throughout the tunnel as desired, and a systematic study was done to identify the causes and possible corrections. Led by

LaRC engineer Zachary Applin, these studies identified flow separation in the diffuser with higher flows toward the outside walls. This unsymmetrical flow into the fan even produced flow reversal in a portion of the tunnel further downstream. Applin developed modifications, particularly training-edge flap additions to the flow control vanes, that alleviated the problem. These, along with a honeycomb flow straightener and four screens just ahead of the contraction, were installed in 1984. That modification program also doubled the space for model setup and testing and added a dynamic test cell for rotor models. The acoustic panels were added to enhance the capabilities for rotorcraft testing, an area where noise reduction had grown in importance.[336]

As enhanced data acquisition and instrumentation systems became available, the team incorporated them into the 14- by 22-Foot Tunnel. Instrumentation, in particular, got smaller and more accurate, allowing more channels of data from a given model. A new technique, developed during the 1980s, uses lasers to measure localized airflows non-intrusively. Known as laser velocimetry (LV), the technique uses laser light focused onto a small point in space, where it reflects off minute particles in the airstream. Doppler methods then compute the velocity of the particles, hence the air, at that point. Usually, the system is set up to measure both vertical and horizontal velocities. Using lenses and a control program, the LV system can traverse the model in almost any pattern desired. It is particularly useful in studies of rotorcraft, where the flow fields around spinning rotors are extremely complex and non-uniform, and in situ sensors would likely interfere with the flow.[337]

While changes in the aircraft design process, consolidation in the aircraft-manufacturing industry, and an overall reduction in the number of new designs in process at any one time have reduced the demand for wind-tunnel testing and closed many tunnels, the 14- by 22-Foot Subsonic Tunnel remains in active service. An ongoing interest in rotorcraft, high-lift devices, noise reduction, and safety during low-altitude flight has kept its test load high in recent years.

As in most other large, subsonic wind tunnels, the 14- by 22-Foot Tunnel uses a single large, variable-speed fan to generate its air flow. (Photo credit: NASA LRC-1993-B701_P-00502)



This drawing identifies the major components of the 14- by 22-Foot Tunnel, after the 1984 addition of its expanded model preparation and rotor test areas. Several different, but interchangeable, model support carts are available to support different types of testing. (Image credit: NASA TP-3008, Fig. 2)

Laser velocimetry, seen here in 1992 being set up with a helicopter model in the 14- by 22-Foot Tunnel, enables accurate measurement of complex flow fields, such as those around spinning helicopter rotors. (Photo credit: NASA LRC-1992-B701_P-03539)

A B-757 airliner model ready for high-angle-of-attack 2000 tests in the 14- by 22-Foot Tunnel. The test section walls are in their closed position for these tests. (Photo credit: NASA LRC-2000-B701_P-01713)

In this 1995 photograph, a Lockheed Advanced Short Take-Off/Vertical Landing aircraft model is mounted on a sting just above the moving-belt ground plane. (Photo credit: NASA LRC-1995-B701_P-06318)

6- BY 19-INCH TRANSONIC TUNNEL

This 2013 aerial view shows Building 585, the cylindrical enclosure for the 6- by-19-Inch Transonic Tunnel, at left. Note the four vertical air reservoirs. Building 580 on the right originally housed Langley's first wind tunnel, but it is now an Air Force office building. (Photo credit: NASA LRC-2013-B701_P-00104)

SIGNIFICANCE

The 6- by 19-Inch Transonic Tunnel (6- by 19-Inch TT) was one of two wind tunnels at Langley—the 6- by 28-Inch Transonic Tunnel being the other—that were converted from existing, but unused, facilities to rapidly and economically increase the center's capability for testing transonic airfoils, particularly designs for the recently developed supercritical airfoil.

DESCRIPTION

The 6- by 19-Inch TT was the product of a rebuilding of the 22-Inch Transonic Tunnel (22-Inch TT) in 1971. The 22-Inch TT was itself the result of a 1952 modification of the 24-Inch High-Speed Tunnel (24-Inch HST), the second of two pioneering blowdown tunnels at Langley that utilized compressed air from the Variable-Density Tunnel (VDT) to propel its airflow to approximately Mach 1. The 24-Inch HST had been built in 1934 as an open-circuit, vertical blowdown tunnel that used VDT air through an annular nozzle to induce a larger flow of air from and to the atmosphere. To reduce water-vapor problems, engineers installed a cylindrical metal enclosure around the tunnel and changed it to a closed-circuit tunnel in 1949. They shortened the exhaust stack by 12 feet at the same time to reduce the enclosure size and improve the tunnel's performance. Movable louvers near the bottom of the enclosure vented a volume of air

to the atmosphere equal to the volume of induction air to maintain a constant volume of circulating test air.[338]

With a growing need for basic research capability, the original test section was replaced with a slightly smaller, octagonal, slotted-wall test section in 1952. Although it measured 20 inches across the test section flats, the tunnel was renamed the 22-Inch TT to avoid any confusion with two other 20-inch tunnels at Langley. The tunnel was changed from induced draft to direct blowdown at that time, returning it to an open-circuit configuration. Compressed air entered a 64-inch-diameter settling chamber at the bottom through a manifold with 16 radial supply pipes. A manually controlled, hydraulically actuated valve regulated the flow. The settling chamber contained turbulence-reducing screens to smooth the airflow, which then passed through a nozzle and into the test section. Air passing through the slots reentered through an annular slot at the top (exit) of the test section, and the total flow passed through the exhaust stack and into the enclosure. The existing louvers at the bottom of the enclosure vented all the air to the atmosphere.[339]

Externally, the 6- by 19-Inch TT is unchanged from the 22-Inch TT. The tunnel and its enclosing structure are identified as Building 585 in Langley's East Area, though its control room is on the second floor of adjacent Building 582. The tunnel is connected to the control room by a steel catwalk that also has a stairway to the ground, which serves as the primary access for both the tunnel and control room.[340]

The test chamber is accessed through two pressure doors. One is through the steel enclosure, and the second is the original (1934) door through the concrete test chamber wall. Within the test chamber is the 6- by 19-inch, vertically oriented test section. Each of its 6-inch walls has four slots. The original concrete test chamber served as the plenum, and it still contains furniture used by technicians during model setup and calibration. A double lock arrangement interlocked the outer door and the control console to ensure that the doors were secured, and no one occupied the test chamber during test runs.[341]

The Mach number was controlled over a range of approximately 0.5 to 1.15 by varying the stagnation pressure, which was determined by the flow-control valve's setting. Thus, operators did not have independent control over Mach and Reynolds numbers. Since the reused original diffuser was less than optimal for this arrangement, the test chamber's static pressure was always close to atmospheric, which yielded fairly low Reynolds numbers that varied with speed. The main data collected were pressure distributions over airfoils, though schlieren and oil-flow visualization studies were also done. In addition, a balance for force and moment measurements was available.[342]

HISTORY

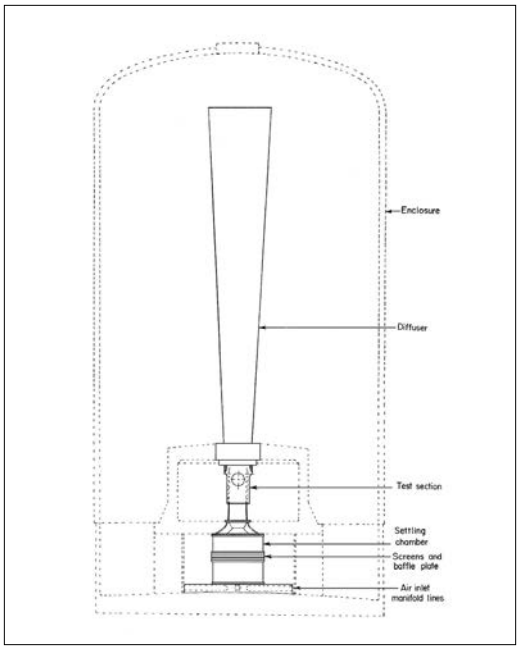
As discussed in the 6- by 28-Inch TT's section, the late 1960s brought an increased need for facilities tailored for testing transonic, especially supercritical, airfoils. This research was well suited to two-dimensional test sections, and Langley engineers investigated several concepts for rebuilding existing, but unused, tunnels. One of these was

the 22-Inch TT, which had closed in 1966, and it became the basis for the first of two conversion projects. Calculations indicated that the tunnel's flow could support a 6- by 19-inch, slotted-wall test section and that the conversion would involve little more than replacement of the original test section, along with upgraded control and data acquisition equipment. The existing test chamber was already sealed, so it would form the plenum around the test section. The test air from the VDT—by then serving only as a pressure vessel—would be adequately dry.

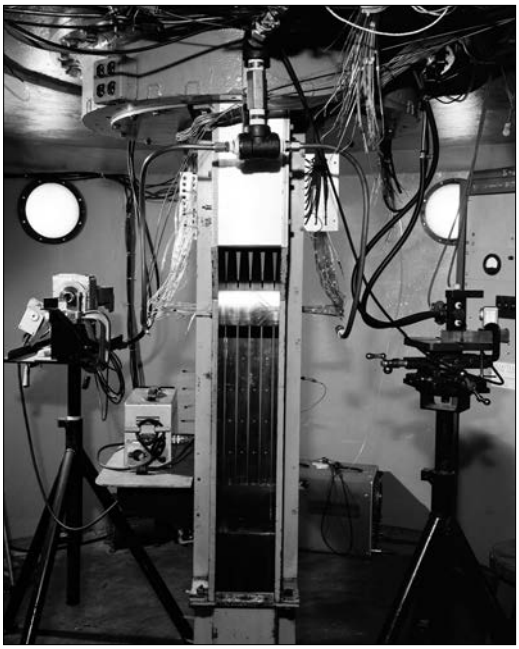
The old test section was removed and the new one fabricated and installed in only a few months. To achieve longer run times than possible using only air from the VDT shell, the engineers decided during the design process to install four new air reservoirs outside Building 582. (The aging VDT shell was retired in 1978.) The renamed 6- by 19-Inch TT opened in early 1971. The conversion had cost less than $30,000, $8,000 less than the cost of a wake-survey rake built for it a year later![343]

As intended, the 6- by 19-Inch TT primarily hosted two-dimensional airfoil studies, but it served as a test bed for wind-tunnel improvement projects as well. One such project involved the design of non-slotted, streamline-matching test section walls using computational fluid dynamics analysis. Walls with a calculated contour were installed in the tunnel for empirical comparison to the calculated performance at Mach 0.9, and the test runs largely validated the calculations. A second project of an entirely different nature investigated the suspension system needed to support supercritical airfoil models for aeroelasticity investigations.[344]

The precise closing date for the 6- by 19-Inch TT is not known, but it operated until the late 1990s, a time when several Langley tunnels were closed for economic reasons. Although not maintained, the tunnel remained intact with relatively little deterioration until its demolition in 2014.[345]

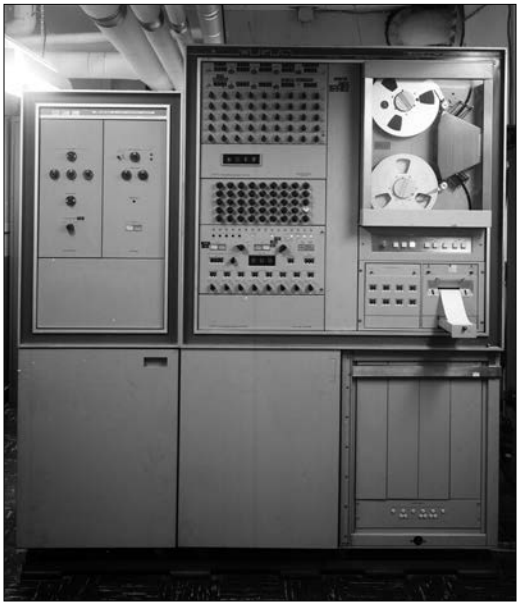


The 22-Inch Transonic Tunnel's test section was replaced to convert it into the 6- by 19-Inch Transonic Tunnel. (Image credit: NASA TN D-7182, Fig. 2)

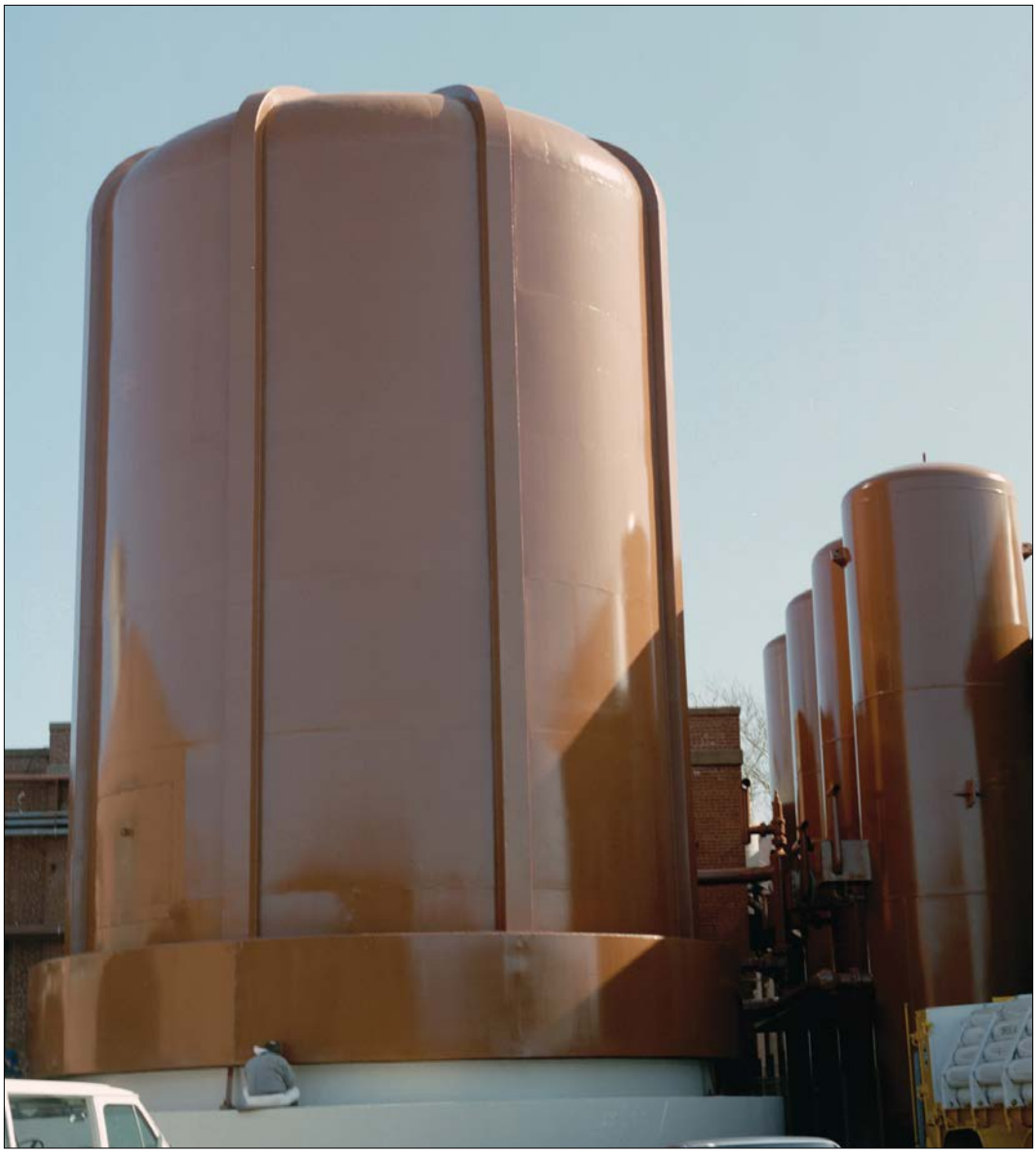


The 6- by 19-inch test section, seen here in 1972, was located within the test chamber. Airflow was upward. (Photo credit: NASA LRC-1972-B701_P-01267)

Pressure doors sealed the outer enclosure and inner test chamber during operation. A keyed interlock system required the outer door to be closed and locked before two keys could be removed and used to unlock the control panel and permit operation. Conversely, the door could not be opened without the keys inserted in the box mounted on the right side of the door frame. (Photo credit: Caroline Diehl, NASA)

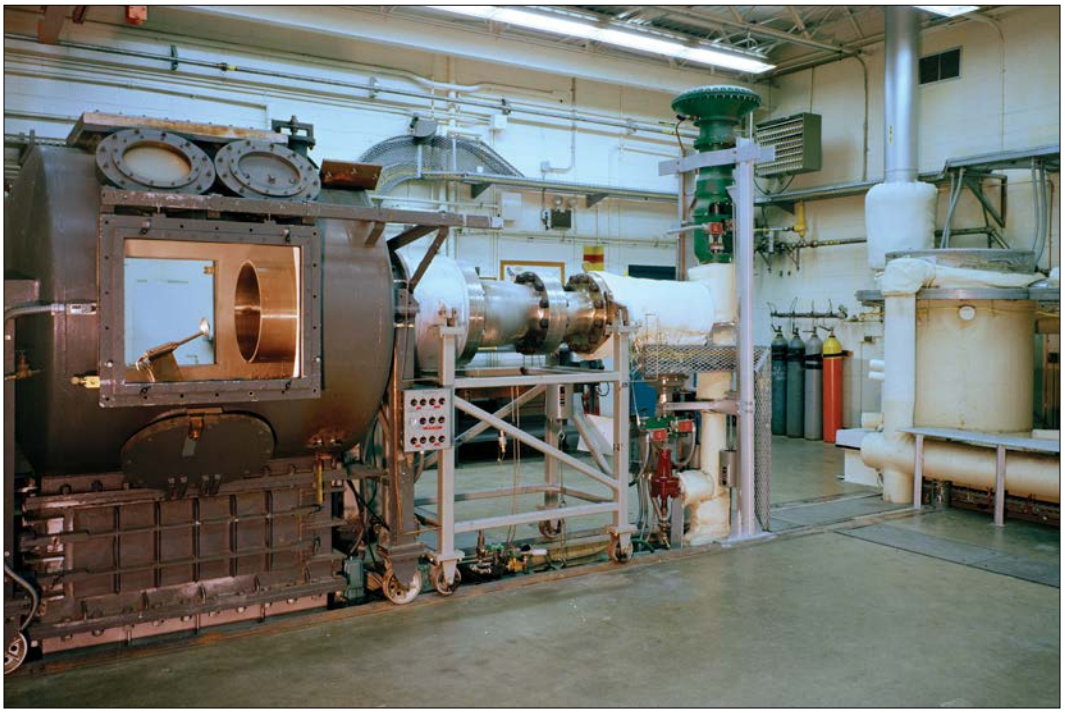


The 6- by 19-Inch Transonic Tunnel's control console was in a second-floor room of adjacent Building 582. Note the keyed interlock device on the lower left panel of this 1972 photograph. Closed-circuit television gave operators their only view inside the test chamber during test runs. The tunnel was accessed from here via a short catwalk. (Photo credit: NASA LRC-1972-B701_P-00876)



A 1992 exterior view of the cylindrical enclosure for the 6- by-19-Inch Transonic Tunnel. (Photo credit: NASA LRC-1992-B701_P-01453A)

20-INCH MACH 6 CF_4 TUNNEL



This 1973 photograph shows the original configuration of the 20-Inch Mach 6 CF_4 Tunnel in Building 1275. Note the control valve on the inlet pipe's tee in the center of this view and the pair of lead-bath heaters at right. (Photo credit: NASA LRC-1973-B701_P-06173)

SIGNIFICANCE

The 20-Inch Mach 6 CF_4 Tunnel (CF_4 Tunnel) was America's only wind tunnel designed specifically to use tetrafluoromethane (CF_4) as its test gas. The use of CF_4, which behaves much like air thermodynamically, allowed researchers to test under hypersonic conditions that cause molecular dissociation in air, but at considerably lower energy levels.

DESCRIPTION

The CF_4 Tunnel, previously known as the Hypersonic CF_4 Tunnel, was a conventional hypersonic tunnel that resulted from an extensive rebuilding of the 20-Inch Hypersonic Arc-Heated Tunnel in the mid-1970s. The main part of the CF_4 Tunnel, including its heaters, control valve, nozzle, test section, and supporting pumps, occupied a portion of Building 1275 in the northwest corner of Langley's West Area, while the supporting gas storage trailers and six permanent bottles, along with two 34-foot, 10-inch-diameter vacuum spheres that receive the exhaust, were located outside the building's north side.[346]

The tunnel operated as a conventional blowdown tunnel, but it employed a recovery system to reclaim its unique test gas for reuse. Following test runs, this system evacuated most of the CF_4 from the vacuum spheres, filtered it to remove impurities, compressed it to 5,000 psi, and returned it to the storage bottles. The system recovered, on average,

80 to 85 percent of the gas, so makeup CF_4 was added as needed from a delivery trailer that remained on-site. Two additional trailers supplied liquid and gaseous nitrogen that was used by the CF_4 Tunnel's gas recovery system.

During a test run, CF_4 from the storage bottles was reduced in pressure to about 2,500 psi, heated by two parallel lead-bath heaters to approximately 1,100°F and passed through screens in a settling chamber, through the axisymmetric Mach 6 nozzle, and into the test section as a 20-inch-diameter open jet flow. (The original test section was a cylinder measuring 5 feet in diameter by 6 feet in length. In 1988, this was replaced by an 8- by 5-foot box of the same length.) From there, the gas passed through a diffuser and water-cooled aftercooler to a pair of vacuum spheres. The maximum run time was 30 seconds, though surface heat transfer tests usually had the model in the jet for less than 5 seconds.

Models were sting mounted, and the sting was supported by a model-insertion mechanism that rotated the model into the test jet after stable flow had been established and removed it prior to shutdown. This avoided damage to the model from strong startup and shutdown shocks. The model's angle of attack was adjustable within a range of –10 to +50 degrees, but it could not be changed during a run. The sides of the test section were hinged access doors secured by latches around their perimeters. The test section had optically clear windows, and shocks could be revealed using a dual-plate holographic interferometer that employed three lasers to produce shadowgraphs, schlieren photographs, or interferographs. Strain gages mounted in the models made force and moment measurements. Stagnation pressure and stagnation temperature were measured in the settling chamber, and pitot pressure was measured just downstream from the nozzle's exit to obtain the tunnel's flow conditions. Surface heat transfer tests used the thin-skin calorimeter method with a thermocouple welded to the inside of the model's skin. Up to 45 channels for pressure measurements and 42 channels for temperature measurements were available, with all data recorded electronically.

HISTORY

The CF_4 Tunnel was designed to investigate high-energy aerothermodynamic phenomena, particularly those around a blunt body during atmospheric entry. The extreme temperature and shock overpressure at hypersonic speeds induce molecular dissociation of the air as it passes through the shock.[347] When this occurs, the specific properties of the "real" gas deviate significantly from those of a so-called "ideal" gas. In particular, the static temperature of a real gas decreases while its static pressure increases, resulting in a significant increase in density. The ratio of this density with the density at normal conditions is typically on the order of 10–20 to 1. All materials possess an intrinsic property known as specific heat *(C)* that, for gases, can be measured with the gas at a constant pressure *(C_p)* or a constant volume *(C_v)*, and each gas has a corresponding ratio of specific heats ($\gamma = C_p / C_v$). The real gas properties of different gases can often be compared by comparing their specific heat ratios.[348]

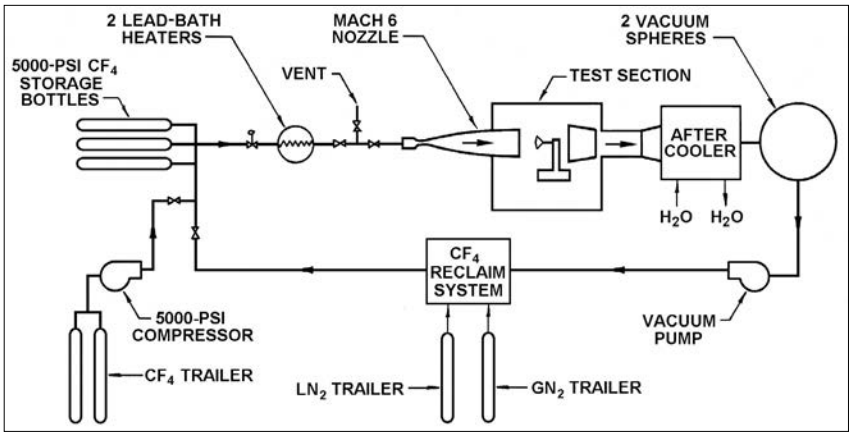
Impulse-type tunnels can generate the high-enthalpy conditions necessary using air as their test gas, but only for fractions of a second, and their data suffer from poor test repeatability. Helium allows high-density shocks to be created in conventional tunnels at relatively low enthalpy,[349] but its ratio of specific heats differs significantly from that of air.

Langley researchers believed that using a gas with a similar ratio of specific heats to that of air, but that would reach the high densities needed for hypersonic research at lower energy levels (enthalpies), might offer an alternative to impulse-tunnel testing. A study recommended CF_4 as such a test gas since its low ratio of specific heats was close to that of air ($\gamma = 1.2$ versus 1.4 for ideal air). Tests showed that this and other properties of CF_4 could be employed to generate useful data at lower enthalpies, such as lower Mach numbers, than possible with air. In 1965, Robert A. Jones and James L. Hunt built a small pilot tunnel to validate the concept. This 3-inch pilot tunnel produced the hoped-for results, and the researchers recommended the construction of a larger, permanent tunnel in 1969.[350]

After an analysis of possible ways to build the tunnel economically, Jones and Hunt recommended that an existing facility, the 20-Inch Hypersonic Arc-Heated Tunnel, which had been built for high-temperature materials testing, be converted into what was originally named the Hypersonic CF_4 Tunnel. Opened in 1972, the later-renamed 20-Inch Mach 6 CF_4 Tunnel was completed at a cost of only $250,000.

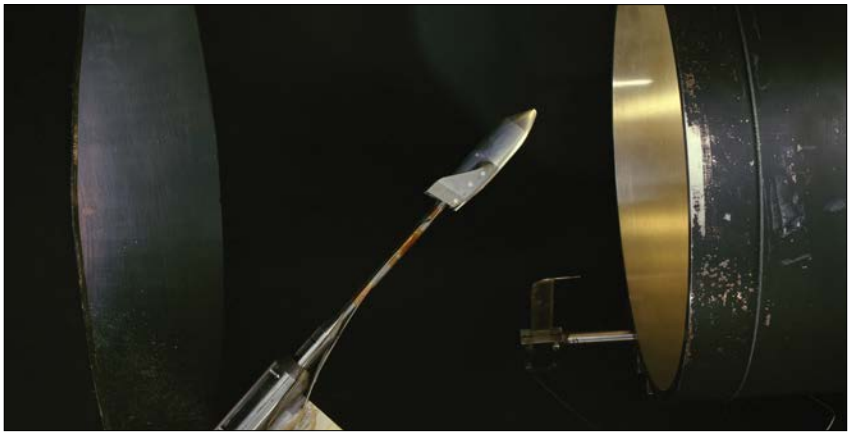
The engineers realized that designing the CF_4 Tunnel to be similar in size to the 20-Inch Mach 6 Tunnel in the Hypersonic Flow Complex would offer a unique opportunity to compare results using CF_4 and air under similar conditions. Comparison tests allowed the researchers to "cross-calibrate" the two tunnels. Testing the same model in both tunnels at Mach 6 provided data for a density ratio range of approximately 5.5 to 12. Ultimately, the researchers would add Langley's 31-Inch Mach 10 Tunnel to the group and extend this range further. These tunnels have been collectively used in several test programs, and they furnished some of the earliest aerodynamic data for the investigation of the Shuttle orbiter Columbia's breakup during reentry on 1 February 2003.[351]

The CF_4 Tunnel underwent several modifications over the years to improve its performance. In 1988, the original test section was replaced with a larger one that enhanced accessibility. This renovation gave engineers an opportunity to perform a detailed study of the tunnel's nozzle, and the analysis recommended changes to the nozzle's contour. A recontoured nozzle was built and installed that delivered a greater mass flow than the original and more closely matched the flow in the 20-Inch Mach Tunnel. To enhance flow stability and productivity, the lead-bath heaters and the gas reclamation system were replaced with state-of-the-art equipment during a 2006 refurbishment. With its unique capabilities and economy of operation, the CF_4 Tunnel remained in service until its demolition in 2017.[352]



This simplified schematic diagram of the 20-Inch Mach CF_4 Tunnel shows its major components and flow path. Except for its test gas and reclaim system, it was a conventional hypersonic tunnel. The reclaim system recovered most of the CF_4 gas from the vacuum spheres after each run and conditioned it for reuse. The original lead-bath heaters shown here were later replaced. (Image credit: NASA TM-78800, Fig. 1)

The 20-Inch Mach CF_4 Tunnel utilized this test chamber, shown here in 1990 with its access door open to reach the model. An open jet of gas flowed across it from right to left. (Photo credit: NASA LRC-1990-B701_P-07172)



A 0.0175-scale X-38 Experimental Crew Recovery Vehicle model is shown here in 1999 in the 20-Inch Mach 6 CF_4 Tunnel. The X-38, though never deployed, was intended to become a lifting body "lifeboat" for the International Space Station. Like the Shuttle orbiter, it was to enter Earth's atmosphere at a high angle of attack. (Photo credit: NASA LRC-1999-B701_P-01079)

0.3-METER TRANSONIC CRYOGENIC TUNNEL

Aerial view of the 0.3-Meter TCT from 1992. (Photo credit: NASA LRC-1992-B701_P-13619)

SIGNIFICANCE

Built as a pilot tunnel for the National Transonic Facility, the 0.3-Meter Transonic Cryogenic Tunnel (TCT) was the world's first pressurized cryogenic wind tunnel. Its functions were to evaluate the performance of a wind tunnel operating at very low temperatures and to gain operational experience under cryogenic conditions. The successful operation of the TCT justified much of the National Transonic Facility's design, and the little tunnel became a useful research tool in its own right.

DESCRIPTION

The TCT, originally named the Pilot Transonic Cryogenic Tunnel, resides in Building 1242A in Langley's West Area. No portion of the tunnel is visible from outside the masonry building. It is a relatively small, closed-circuit tunnel with its return duct located directly below its test section and diffuser, giving it a small footprint with a

nominal length of approximately 40 feet. Its fan and drive motor are located at one of the vertical turns (Corner 2) that form its northern end. The tunnel is chilled by the injection of liquid nitrogen into its diffuser section. The liquid nitrogen evaporates quickly, absorbing heat from the gaseous nitrogen test medium, which has similar properties to atmospheric air in the transonic speed range.

The TCT is constructed with aluminum rather than the usual steel because aluminum's mechanical properties are more suitable for cryogenic temperatures. The tunnel sections are connected with flanged joints sealed by gaskets. Most of the tunnel is externally insulated with blown urethane to minimize heat gain from the environment. The urethane is not bonded to the tunnel walls, but it is separated by two layers of fiberglass cloth that accommodate the tunnel's thermal contraction and expansion. An external polyester vapor barrier prevents the urethane from absorbing moisture from the atmosphere. The tunnel is mounted on steel A-frame supports, but it is anchored only to the support adjacent to Corner 2. The other supports have sliding saddles to allow for thermal contraction and expansion, which can be as much as 2.5 inches overall. The tunnel-to-support interfaces are stainless steel.[353]

Liquid nitrogen, stored in on-site tanks at –321°F, is injected into the airstream through up to four nozzles located in the diffuser between the test section and fan, though only two nozzles are typically used. This location promotes rapid evaporation, since this section has the lowest pressure of any location in the tunnel, and the fan then promotes thorough mixing to obtain a homogeneous test gas before the flow reaches the settling chamber and screens. An exhaust system removes a volume of gaseous nitrogen equivalent to that injected to both remove internal heat and control the pressure. Temperatures from –320 to +130°F and pressures between 1 and 6 atmospheres (14.7–88 psia) can be maintained in the TCT.[354]

The TCT is currently equipped with an adaptable-wall test section (AWTS) that uses 30 computer-controlled jacks to contour flexible top and bottom walls to match calculated streamlines. Its nominal cross section is 13 by 13 inches (approximately 0.3 meters square). The test section and jacking arrangement are housed in a rectangular plenum that is part of the pressure vessel. Airfoil models are supported on either, or both, sidewalls by rotary mountings that allow the pitch (angle of attack) to be adjusted from –9 to +32 degrees. Two other test sections have been used in the past. They are interchangeable with the AWTS and could be used again if needed.[355]

The TCT's 12-blade aluminum fan and 3,000-horsepower, variable-frequency drive motor generate test speeds from Mach 0.1 to Mach 0.9 in the AWTS, although speeds as high as Mach 1.3 were possible with the original, slotted-wall test section. Seven prerotation vanes and 15 counter vanes minimize swirl in the flow. This variable-frequency AC motor was an early use of such a motor in place of DC motors and motor-generator sets in variable-speed wind tunnels. It is water-cooled to allow continuous operation throughout its 600- to 5,600-revolution-per-minute speed range.[356]

Advanced two-dimensional airfoils are the most common models tested in the TCT with the AWTS installed. Since pressure profiles are the primary data desired from such tests, the TCT is equipped with an electronically scanned pressure (ESP) system to record data several times a second from up to 450 ports, though typical tests involve about 100 ports. A wake rake referenced to tunnel pressure yields drag data, and thermocouples can be used for a variety of temperature measurements.[357]

HISTORY

The TCT was a product of Langley's long pursuit of higher Reynolds numbers in wind tunnels, starting with the Variable-Density Tunnel (VDT) of 1922. As discussed in the VDT section, the Reynolds number is the key to achieving dynamical similarity between a model in a wind tunnel and a full-sized airplane. At atmospheric pressure, the model's Reynolds number will always be less than that of the airplane. The VDT and other pressurized tunnels used compressed air, or other test gases, to raise the Reynolds number and generate data close to in-flight values, but increasing speeds resulted in Reynolds numbers that became impractical to reproduce in wind tunnels through pressurization alone.

As early as 1945, British researcher R. Smelt theoretically predicted that substantially lowering the operating temperature in a wind tunnel would reduce its size and power requirement for given Mach and Reynolds numbers. Cryogenic (very-low-temperature) technology was not readily available to test Smelt's claim for about two decades, but once it was, researchers at Langley and elsewhere began to experiment with it. At first, Langley's main interest was in the possible combination of a cryogenic tunnel with a magnetic model suspension system under development, since it would permit a smaller tunnel, but they soon saw another application of the technology. Instead of reducing tunnel size for a given Reynolds number, one could increase the Reynolds number in a given size of tunnel.[358]

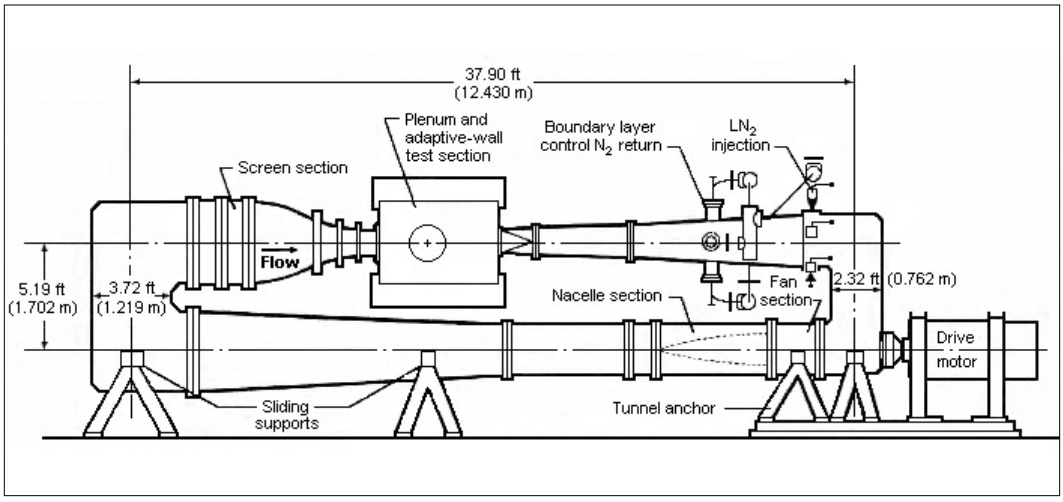
The Langley engineers began experimenting with a small tunnel into which they injected liquid nitrogen at –321°F. Results were encouraging, and NASA approved construction of the Pilot Transonic Cryogenic Tunnel in 1972. Design and construction proceeded quickly, and the tunnel opened only nine months later in September 1973. The new tunnel quickly validated its engineers' design predictions, and it generated unprecedented Reynolds numbers—up to 100 million per foot. Within a year, NASA realized that this tunnel was useful not only for cryogenic tunnel development, but for serious transonic research as well, so "Pilot" was dropped from its name and replaced with its approximate size. Metrification was in vogue in 1974, making "0.3-Meter" the preferred dimension. Unlike the 14- by 22-Foot Tunnel, which was also given a metric name when built but later renamed with English units, the TCT has retained its metric name.[359]

The TCT has utilized three basic test sections since its opening in 1973. The original was an octagonal, slotted-wall design within a cylindrical plenum. It measured 13.5 inches between flats by 33.75 inches long. Slots were at the intersections of the dihedral angles. This test section normally operated up to Mach 1.06, but it was capable of Mach 1.3 at higher pressures. The relatively small size of the TCT made it better suited to testing two-dimensional airfoils than three-dimensional models, so a two-dimensional test section was installed in 1975. Since the TCT had been designed with interchangeable test sections in mind, it had flanged connections that made alternative sections easy to build and install. The two-dimensional test section, with slots in its floor and ceiling, proved to be ideal for airfoil testing, generating Reynolds numbers of up to 50 million on a 6-inch-chord airfoil. Additional development work resulted in the AWTS, with its flexible ceiling and floor, in 1986. The AWTS is not slotted, so its maximum operating speed is Mach 0.9. This is, however, right where most of the world's commercial and military aircraft routinely fly. Its flexible walls that match streamlines allow model chord lengths of up to 1 foot and Reynolds numbers of up to 100 million.[360]

Research projects in the TCT have primarily been in two areas: basic research into the use of cryogenic gases in wind tunnels, and preliminary testing of advanced airfoil concepts at high Reynolds numbers. The basic research has included such topics as boundary-layer removal and the use of flexible test section walls. One program investigated the use of sulfur hexafluoride (SF_6) as a test gas at ambient temperatures because of its high density but found it to offer few, if any, advantages over cryogenic nitrogen. Most airfoil evaluations have focused on pressure distributions across the models and produced extensive amounts of data at various speeds and angles of attack.[361]

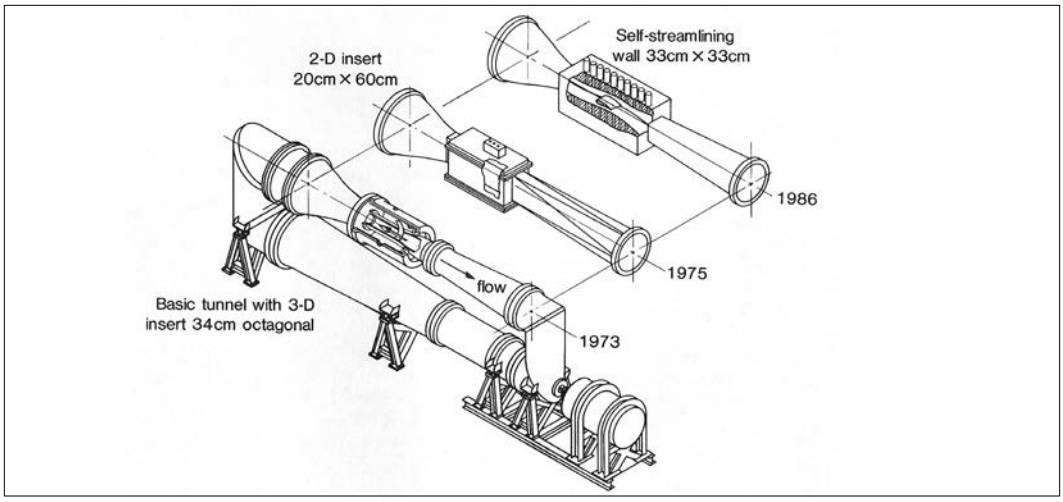
Although one justification for the TCT was its use with a magnetic suspension and balance system then under development at Langley, the University of Virginia, and the Massachusetts Institute of Technology, magnetic suspension did not prove to be practical. Consequently, such a system was never installed in the TCT, though a preliminary design for a magnetic suspension test section was developed.[362]

The excellent performance of the TCT and the high quality of its data demonstrated the value of cryogenic testing, and these became the primary justification for what became Langley's National Transonic Facility, a cryogenic tunnel over seven times larger than the TCT. In 2005, the TCT was placed in standby status. Maintained in operational condition, it has hosted occasional test programs since then, and NASA currently has no plan to retire the tunnel.

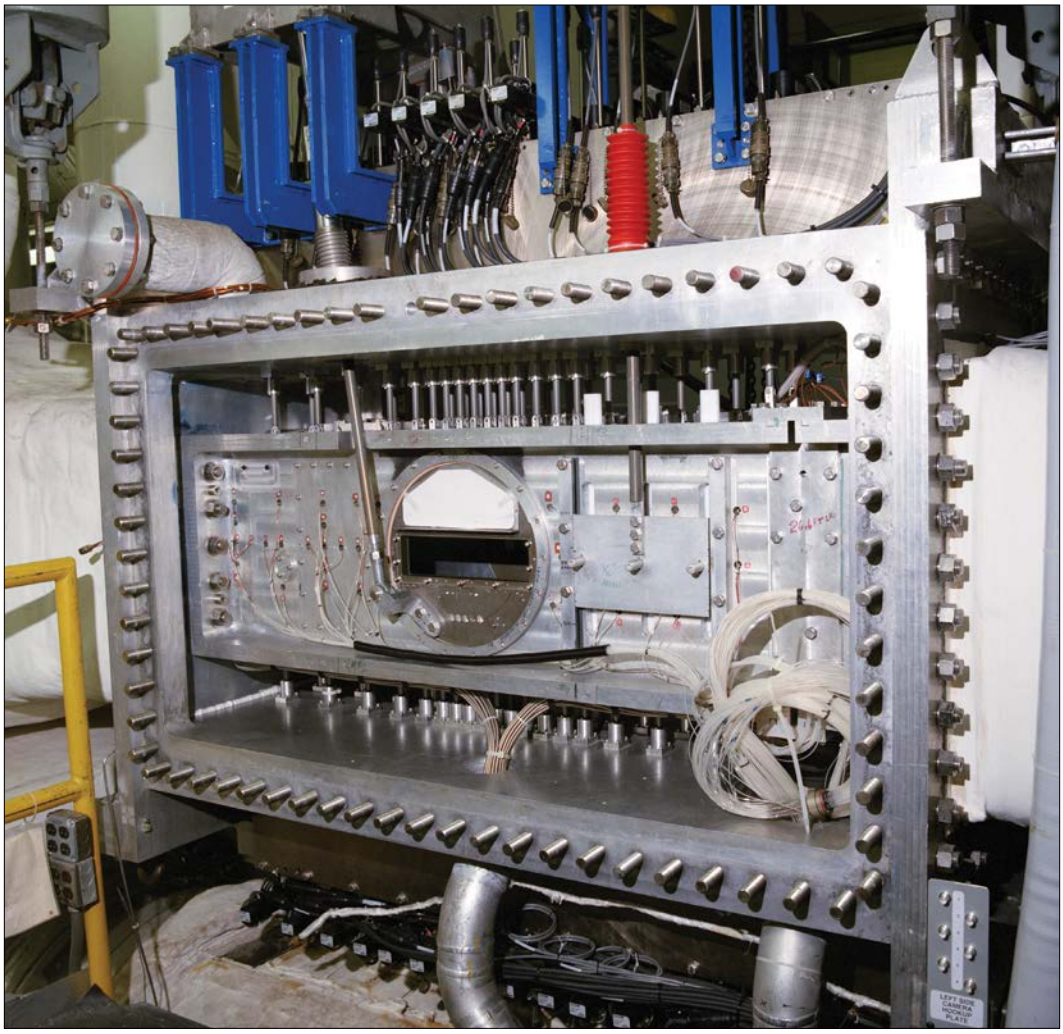


This drawing shows the general arrangement of the 0.3-Meter TCT with the adaptable-wall test section. Note the vertical orientation of the circuit and the injectors for liquid nitrogen that chills the tunnel. The gaseous nitrogen exhaust ducts from near the lower left corner and plenum are not shown. (Image credit: NASA TN D-8304, Fig. 1)

The upper portion of the 0.3-Meter Transonic Cryogenic Tunnel is seen in 1985 showing (left to right) the nozzle contraction, adaptable-wall test section with gaseous nitrogen exhaust ducts, and liquid nitrogen injector section. (Photo credit: NASA LRC-1985-B701_P-09893)



This evolution of the 0.3-Meter TCT led to the self-streamlining, or adaptable-wall, test section in 1986, with top and bottom walls that adjust to follow the contours of streamlines around model airfoils, thus minimizing the effect of the tunnel on test results. (Image credit: NASA TN D-8304, Fig. 27)



The 0.3-Meter Transonic Cryogenic Tunnel's adaptable-wall test section is visible in this 2000 photograph with one side of the plenum removed. Thirty jacks shape the top and bottom walls of the test section to match the flow streamlines around the model under test. Note the tunnel's external insulation. (Photo credit: NASA LRC-2000-B701_P-00281)

6- BY 28-INCH TRANSONIC TUNNEL
20-INCH VARIABLE SUPERSONIC TUNNEL

Interior view of the 6- by 28-Inch Transonic Tunnel in 1974. (Photo credit: LRC-1974-B701-P-00952)

SIGNIFICANCE

The 6- by 28-Inch Transonic Tunnel was one of two wind tunnels at Langley—the 6- by 19-Inch Transonic Tunnel being the other—that were converted from existing, but unused, facilities during the 1970s to rapidly and economically increase the center's capability for testing transonic airfoils, particularly designs for recently developed supercritical airfoils.

DESCRIPTION

The 6- by 28-Inch Transonic Tunnel (6- by 28-Inch TT) resulted from a major rebuilding of the 20-Inch Variable Supersonic Tunnel (VST) in 1974. As originally completed in 1961, the VST was a horizontal blowdown tunnel approximately 80 feet long, fabricated from steel plate, and mounted atop the 26-Inch Transonic Blowdown Tunnel (TBT) in Building 583 in Langley's East Area. The VST received air that originally had been compressed and dried for use in the Low-Turbulence Pressure Tunnel (LTPT) next door in Building 582-A and passed through the settling chamber of the TBT. A hydraulically operated air pressure regulation system upstream from the TBT employed three servo

valves to control stagnation pressure and, thus, Reynolds number, in either the TBT or VST, even as supply pressure decreased.[363]

From the TBT's settling chamber, a valve in a connecting duct routed the flow to the VST's 84-inch-diameter settling chamber, which was directly connected to its variable supersonic nozzle and 20- by 20-inch test section. An electric resistance heater provided air temperatures of up to approximately 200°F to prevent air liquefaction, and a second valve in the TBT's diffuser prevented airflow through that tunnel. The VST's settling chamber contained a conical, porous baffle plate and three 30-mesh screens. The VST's two-dimensional nozzle, with a contraction ratio of about 32:1, used adjustable top and bottom walls for speed variation, and it could generate test speeds of Mach 2.0–4.5. Depending on speed, the air supply was adequate for runs between 40 and 300 seconds long. Air leaving the VST's test section passed through a diffuser with an adjustable second minimum and into a large vertical stack shared with the TBT that exhausted to the atmosphere through the building's roof. Sound-attenuation baffles in the stack reduced exterior noise.[364]

After being rebuilt into the 6- by 28-Inch TT, the tunnel—one of the few tunnels whose name had its width dimension listed before its height—retained the same basic configuration and mode of operation, although with modernized controls and data acquisition equipment. The main physical changes were a new nozzle and slotted-wall test section configured for transonic testing. The top and bottom walls each have four slots, and, as with all slotted-wall test sections, this one is enclosed within a plenum, 76 inches in diameter by 150 inches long, which necessitated access hatches in both the plenum shell and test section walls. The 9.5-inch-diameter test section sidewall hatches include model-support fittings with adjustable angle of attack. Since the tunnel was relatively small, access to the test section through these hatches was confined to say the least.[365]

The by 28-Inch TT included a novel control element, two "choker doors" located at the test section's exit. Automatically controlled, these hydraulically actuated doors slid in and out horizontally to control Mach number. Since Mach 1 always occurred at the door opening, that open area controlled mass flow through the tunnel and, thus, the test section Mach number. This functioned independently from the pressure-control system noted above that provided Reynolds number control.[366]

HISTORY

In the mid- to late 1950s, much of the NACA's attention was focused on supersonic and hypersonic flight, primarily for military aircraft, and Langley's tunnels for those regimes were well booked with a variety of projects. A large portion of these involved actual or proposed aircraft designs, and little research time was available for basic airfoil research. Since basic airfoil research could be done effectively using relatively small, two-dimensional models and tunnels, Langley engineers looked for quick, inexpensive ways to provide some additional capacity.

The 26-Inch Transonic Blowdown Tunnel (TBT) in Building 583 had been built in 1950 to utilize dry, compressed air from the Low-Turbulence Pressure Tunnel (LTPT) located next door in Building 582-A. Since the TBT was not fully booked, the engineers envisioned a second tunnel mounted on top of it that could be connected to use the same air source, with the tunnels operating on alternating schedules. This concept became the 20-Inch Variable Supersonic Tunnel (VST) with a range of Mach 2.0–4.5, and its design was essentially finalized in 1957.[367]

The NACA was folded into the new NASA organization the following year, and NASA's priorities were substantially different from those of the NACA. The reorganization process gave projects like Langley's VST a low priority, and its construction was delayed, but it finally became operational in 1961. The tunnel was successful and useful, but contemporary events and changes in aviation goals cut its service life short. With the operational SR-71 and experimental XB-70, the Air Force stopped pushing the speed envelope of airplanes at about Mach 3. Missiles and spacecraft would certainly go much faster, but by 1960, there appeared to be little, if any, need for combat aircraft to do so, especially considering the enormous development and operating costs involved. (The SR-71, operating in reconnaissance service until 1990, was the only American airplane to operate extensively above Mach 2.) Accordingly, interest in supersonic research waned, and Langley closed the VST in 1965.

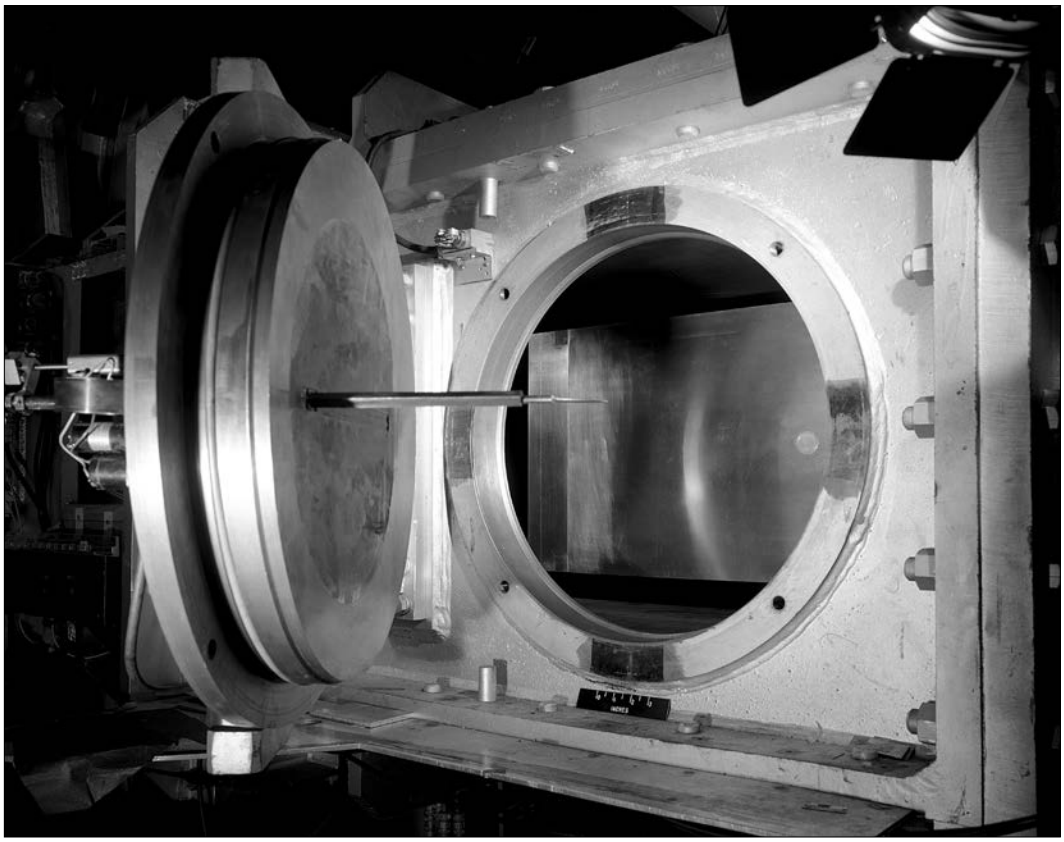
The introduction of jet-powered transports in 1957–58, followed by an explosive growth in the airline industry during the 1960s, also changed aviation priorities. The B-707 and DC-8, along with all their commercial descendants other than Concorde, operate in the low-transonic regime. The airlines' desire to convert entirely to jet propulsion on routes of all lengths, plus their continuing quest for improved operating efficiency, dramatically increased the need for transonic research capability as manufacturers hurried to introduce a wide variety of new airplanes suited to specific airline needs. A third event near the end of the decade, Richard Whitcomb's development of the supercritical airfoil, opened another path of transonic research that was intensively pursued into the 1970s.[368]

All of this, not to mention the drastic rise in fuel price in the mid-1970s, placed transonic research back in the forefront of aviation research, and NASA's engineers had to again seek ways to increase wind tunnel capability quickly. At Langley, two closed tunnels proved to be suitable for conversion into facilities for transonic airfoil research. They were the 22-Inch TT[369] and the VST. Langley rebuilt the former into the 6- by 19-Inch TT in 1971, but this tunnel lacked the ability to control Reynolds and Mach numbers independently, so engineers turned to see if this could be achieved with the VST. A study indicated that it could and that the VST's conversion would require only a replacement of the test section with a new design. The new test section did necessitate improved controls for the choking doors, and the engineers took the opportunity to upgrade data acquisition equipment at the same time.[370]

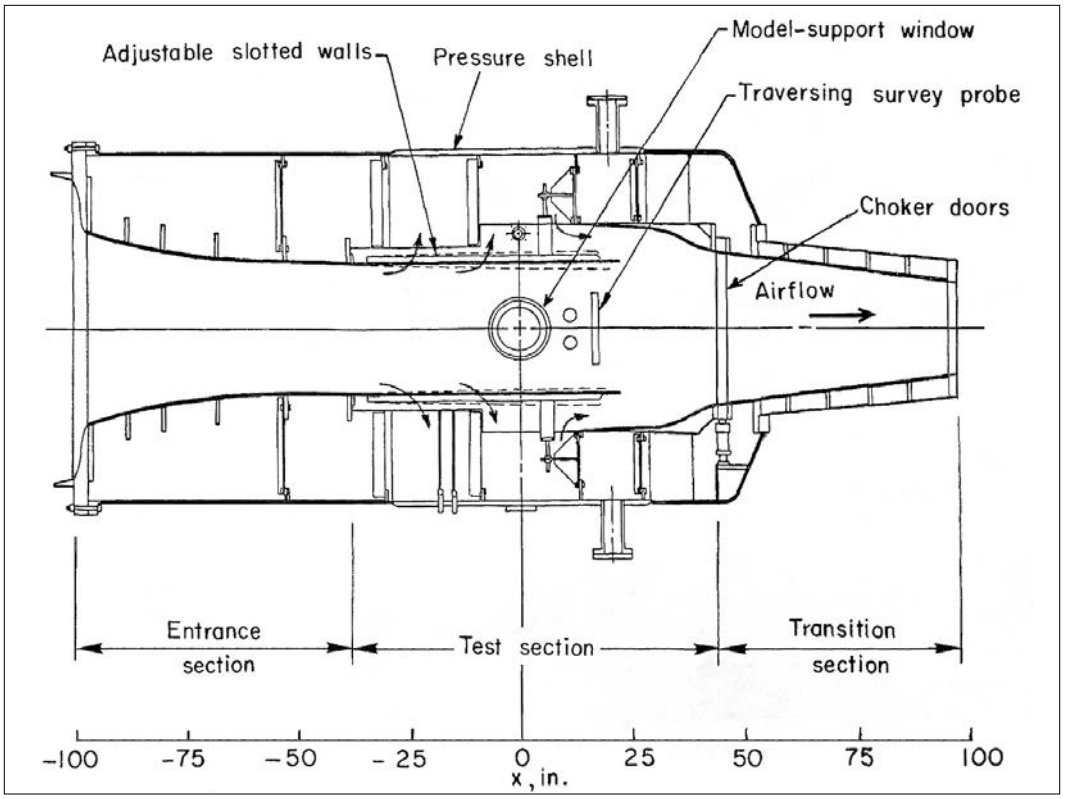
The converted tunnel, renamed the 6- by 28-Inch Transonic Tunnel (6- by 28-Inch TT), returned to service in 1975, and it quickly demonstrated the desired performance. Because it was intended for tests of two-dimensional airfoils, pressure distributions across the airfoil and its wake were the primary data desired, and the tunnel could monitor 64 channels, plus one for the traversing wake-survey probe. The schlieren flow-visualization system from the VST was retained as well.[371]

The 6- by 28-Inch TT served in its intended capacity testing two-dimensional airfoils into the 1990s, and its projects included tests of rotorcraft airfoils as well as those for fixed wings. A modification program about 1980 gave the tunnel redesigned test-section slots and adjustable reentry flaps that improved its flow characteristics.[372]

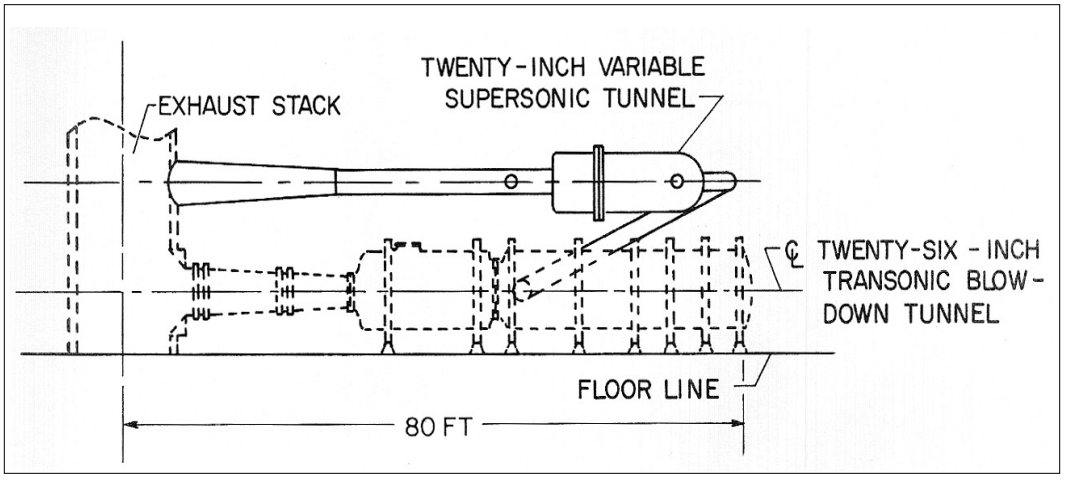
Its precise deactivation date is unknown, but the 6- by 28-Inch TT was listed as closed in 1998. The second minimum and diffuser sections were removed, but the tunnel's test section and settling chamber remained intact, though unmaintained. The tunnel's control console components remained not only intact, but largely energized.[373] The tunnel was removed during the demolition of Building 583 in October 2014.[374]



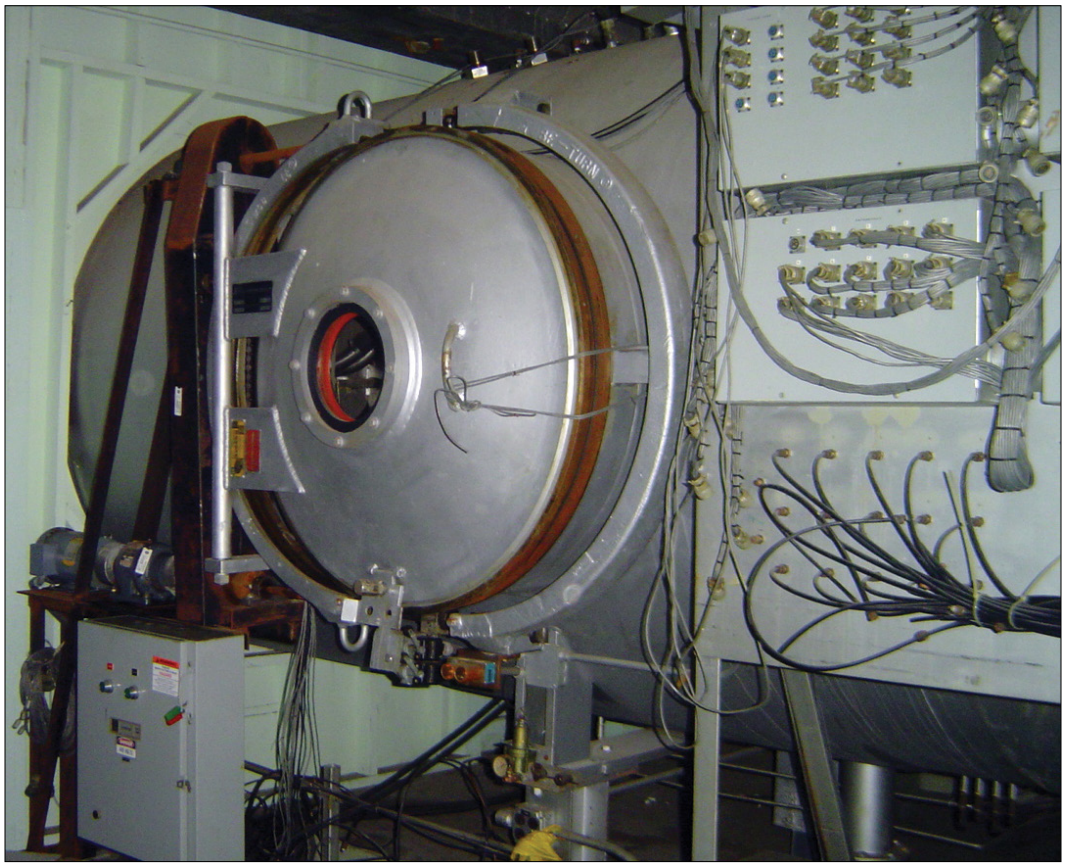
The test section of the 20-Inch Variable Supersonic Tunnel with its hatch open in 1963. Note the airfoil model mounted on the hatch. (Photo credit: NASA LRC-1963-B701_P-00800)



The 6- by 28-Inch Transonic Tunnel's test section. Note the slotted top and bottom walls and choker doors. (Image credit: NASA TN D-8070, Fig. 4)



Although located in the same position as the 20-Inch Variable Supersonic Tunnel and operating in much the same manner, the 6- by 28-Inch Transonic Tunnel utilized a different test section with improved access and performance tailored to the transonic regime. Much of the tunnel's exhaust duct has been removed. (Image credit: Caroline Diehl, NASA)



This 6- by 28-inch test section replaced the 20-inch test section to create the 6- by 28-Inch Transonic Tunnel. Only its plenum and outer access hatch are visible here. (Photo credit: Caroline Diehl, NASA)

This console managed control and data acquisition for the 6- by 28-Inch Transonic Tunnel. (Photo credit: NASA TN D-8070, Fig. 1b)

SCRAMJET TEST COMPLEX

This 1991 aerial view of the Scramjet Test Complex Building 1221 shows the test cell structure, vacuum sphere, vertical air bottles, and gas trailers. (Photo credit: NASA LRC-1991-B710_P-04452)

SIGNIFICANCE

The Scramjet Test Complex (STC) is Langley's primary facility for the evaluation of hypersonic air-breathing engine concepts. Four wind tunnels operated by the Hypersonic Air-Breathing Propulsion Branch are used to test engine and component designs at speeds of up to Mach 8 and simulated altitudes as high as 150,000 feet.

DESCRIPTION

The STC is centered in Building 1221 in Langley's West Area, which the Hypersonic Air-Breathing Propulsion Branch (HAPB) shares with other facilities. Three of the four wind tunnels directly controlled by the HAPB reside in Building 1221, while a fourth, the Arc-Heated Scramjet Test Facility (AHSTF), occupies Room B-111 in adjacent Building 1247. Building 1221 is primarily a steel-frame, brick structure that has both two-story and high-bay, single-story areas, but its D area contains specialized test cells that feature different construction methods and materials.[375]

Two of the HAPB's tunnels are housed in test cells having 2-foot-thick, reinforced-concrete walls and ceilings to make them fire- and explosion-resistant, since the tunnels utilize high-pressure air and hydrogen fuel. An aisle separates them. Each test cell measures 16 feet wide by 16 feet high by 52 feet long and has two extensions through the D area's raised roof. One is topped with a fan that force-ventilates the entire cell during operation, and the extension at the other end serves as an exhaust chase. The tunnel in each cell can exhaust to a vacuum sphere through a 48-inch duct or to the atmosphere through a 72-inch stack. The tunnel's atmospheric exhaust is an open jet into the stack, which assists the fan with cell ventilation when in that mode. A steam ejector is used to evacuate the 70-foot-diameter vacuum sphere prior to and during test runs in vacuum mode.

In a hall just outside the test cells, a manifold emerges through the floor, and smaller pipes from it penetrate the test cell walls. This system conveys 550-pound-per-square-inch-absolute compressed air from a bottle field outside the building to the tunnels. Gaseous hydrogen and oxygen are piped into the cells from trailers parked outside. Gaseous nitrogen is piped into the test cells from a storage tank located outside the building. Prior to entering the test cells, the nitrogen is regulated to 230 psia, while the hydrogen and oxygen are regulated to 720 psia. Hydrogen is also the primary fuel for combustion within the engine, and oxygen is available to support research involving jet-to-rocket transition. Nitrogen is used to purge the system after runs.

Test Cell 1 houses the Combustion-Heated Scramjet Test Facility (CHSTF), which delivers airflow around and through a complete engine nacelle. Test Cell 2 houses the Direct-Connect Supersonic Combustion Test Facility (DCSCTF), a tunnel that connects directly to a test combustor's inlet and exhaust to simulate only airflow inside an engine. An adjacent room houses control and data acquisition equipment. Room C-205 on the building's second floor houses the Mach 4 Blowdown Facility (M4BDF), an unheated tunnel used for testing engine inlet designs. The AHSTF, located in adjacent Building 1247, employs the utilities of that structure. Each of these tunnels is described in further detail below.

Two additional facilities are utilized by the HAPB, although they are considered separate facilities apart from the STC. These are the 8-Foot HTT at Langley and the HYPULSE Facility in Ronkonkoma, New York. HYPULSE was originally Langley's 6-Inch Expansion Tube, but it was transferred to GASL's Ronkonkoma facility in 1983. Each of these tunnels is discussed in its own section.

HAPB researchers have also used two other Langley wind tunnels that no longer exist, the Ceramic Heated Combustion Facility, also known as the 11-Inch Ceramic-Heated Tunnel, and the 7-Inch HTT. These tunnels are also described in their own chapters.

HISTORY

As with hypersonic aerodynamic research, hypersonic propulsion research in America has endured periods of intense activity separated by periods of virtually no interest and

funding. The problems are daunting for both materials and fluid dynamics/combustion at speeds above Mach 5, but long-term development projects rarely maintain political support. Accordingly, the support for construction and use of hypersonic research facilities has been sporadic.

During the 1950s, ramjets, which use contoured inlets to compress incoming air with no moving parts, showed great promise as supersonic engines, and several missiles utilized them. As in turbojet engines, inlet air was compressed, but slowed to subsonic speed, before it entered the combustor. Little was known about initiating and maintaining stable combustion in flows at Mach 1 and above, but engineers began to theorize that supersonic combustion was possible, even though they had little concept of what such an engine might look like.

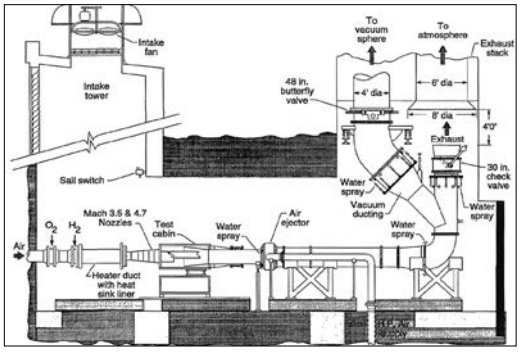
In the early 1960s, NASA and the Air Force began work to investigate supersonic combustion, and this work suggested that a supersonic-combustion ramjet, or "scramjet," would be practical for speeds in the Mach 4–8 range. The tests supporting this conclusion were performed in direct-connect combustor facilities, primarily at the Air Force's Arnold Engineering Development Center in Tullahoma, Tennessee, and at certain engine manufacturers. This led to a NASA project to develop the Hypersonic Research Engine (HRE). When the HRE project ended in 1975, considerable progress had been made on an engine enclosed within a cylindrical nacelle, as well as a second design integrated with an airframe, though neither had made a powered flight.[376]

Following a decade of disinterest, President Ronald Reagan's support of a National Aero-Space Plane (NASP) spurred further research, but the vehicle proved to be impractical, and research funding dried up again after the project was canceled in 1995. In spite of this, NASA decided to continue scramjet development with a series of uncrewed experimental aircraft in its Hyper-X Program. The most recent of these planes is the X-43A, which set a world record for air-breathing vehicles of Mach 9.68 on 16 November 2004. Work continues slowly on the next phase of this project, which will include changing from hydrogen to a more conventional hydrocarbon fuel.[377]

The main research interest at the present has to do with the combustion process, specifically achieving rapid ignition and a stable burn at altitude and speed. Basic research on combustion problems is best done in direct-connect tunnels, where all other engine variables can be eliminated. Thus, the DCSCTF stays reasonably busy, and the AHSTF was modified in 2008–09 to support a direct-connect mode of operation. While the AHSTF has tested a number of integrated airframe-engine combinations over the years, these tests are now run in the 8-Foot High-Temperature Tunnel, which can accommodate larger models.[378]

Tunnels in the Scramjet Test Complex

Test Cell 1, Combustion-Heated Scramjet Test Facility

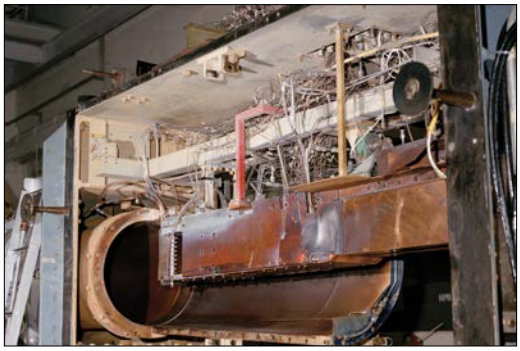


The Combustion Heated Scramjet Facility occupies Test Cell 1 in Building 1221. Water sprays cool the exhaust to maximize the vacuum sphere's capacity. (Image credit: AIAA-2001-367, Fig. 1)

The Langley Combustion Heated Scramjet Facility (CHSTF), completed in 1978, is a horizontal, blowdown tunnel that uses a hydrogen-fueled heater to obtain the flight stagnation enthalpy required for scramjet engine testing. Incoming air is enriched with oxygen before the introduction of hydrogen and combustion to yield a test gas with the same oxygen content as atmospheric air. The heater is water-cooled. The CHSTF normally operates at stagnation pressures between 50 and 500 psia and at stagnation temperatures between 840 and 2,540°F. Test gas mass flow rates range from 15 to 60 pounds per second.

Nozzles are available for Mach 3.5 and 4.7. Both nozzles have square cross sections and are contoured to exit dimensions of 13.26 by 13.26 inches. The nozzle flow exhausts as a free jet into the test section, which measures 42 inches high by 30 inches wide by 96 inches long. The nozzle flow forms a free jet that passes around and through the test engine model.

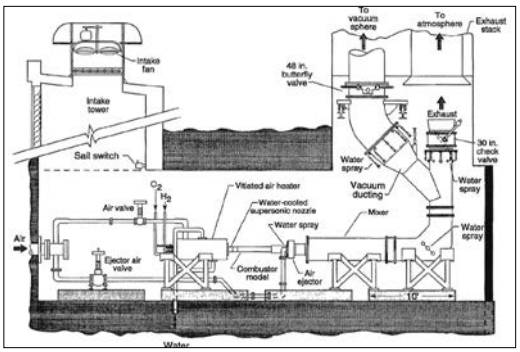
Either gaseous hydrogen or gaseous ethylene may be used as the primary fuel in the scramjet engines. To aid ignition, a 20/80 mixture of silane and hydrogen can be used. Its exhaust is routed to the atmosphere. Once stable combustion has been achieved in the engine, valves redirect the exhaust flow to the vacuum sphere, which is evacuated to simulate the desired altitude. Water sprays cool the gas to maximize the vacuum sphere's capacity.[379]



With one side of the CHSTF's test cabin removed, a scramjet model is ready for testing in 1993. Note the tunnel's circular exhaust duct opening at left. Water sprays and an air ejector are located in the exhaust duct farther downstream to cool and facilitate the flow. (Photo credit: NASA LRC-1993-B701_P-13974)

The CHSTF and Test Cell 1 are essentially complete and intact, but the facility has been in standby status since early 2007.

Test Cell 2, Direct-Connect Supersonic Combustion Test Facility



Test Cell 2 in Building 1221 contains the DCSCTF. Note how the combustor model actually becomes a part of this tunnel, instead of a model inside a test section. All test air flows through the model. (Image credit: NASA DCSCTF071498)

The Direct-Connect Supersonic Combustion Test Facility (DCSCTF) is a horizontal, blowdown tunnel that uses a hydrogen-fueled heater to produce conditions equivalent to those at the entrance to a scramjet's combustor. Built during the early 1970s, it was designed specifically to test supersonic combustors for possible use in scramjet engines, and it is termed a "direct-connect" tunnel because the tunnel's nozzle delivers a flow that simulates the conditions at the exit of a scramjet's compression section directly to the combustor. No airflow goes around the engine. This allows combustor performance, particularly ignition and flame stability, to be evaluated in isolation, apart from the engine's inlet performance and exhaust nozzle.

With four available nozzles, the DCSCTF can produce speeds of Mach 2.0–2.7, internal engine conditions equivalent to those at flight Mach numbers of 3.5–7.5. All these nozzles are two-dimensional and water-cooled. Incoming air is enriched with oxygen before the introduction of hydrogen and combustion to yield a test gas with the same oxygen content as atmospheric air. Since hydrogen combustion is involved, this vitiated-air test gas also contains water vapor and small amounts of nitrogen compounds. The DCSCTF normally operates at stagnation pressures between 115 and 500 psia and stagnation temperatures between 1,140 and 3,340°F. Mass flow rates of the test gas range from 1 to 20 pounds per second.

Gaseous hydrogen is the primary fuel for the combustor under test, though other gaseous and liquid hydrocarbon fuels have been used. In 2003, a heated liquid fuel system was added that can deliver fuels such as JP-7 and JP-10 to the test combustor at temperatures of up to 1,350°F. To aid ignition, a 20/80 mixture of silane and hydrogen can be used. Silane, which burns spontaneously in air, is added at start-up to ensure ignition, then shut off, after which the combustor continues to operate on a single fuel. Its exhaust is routed to the atmosphere. Once stable combustion has been achieved in the combustor, valves redirect the exhaust flow to the vacuum sphere, which is evacuated to simulate the desired altitude. Water sprays cool the exhaust to maximize the capacity of the vacuum sphere.

Originally designed to test scramjet combustors, the DCSCTF has, since the mid-2000s, also been utilized to test a strut-ducted hydrogen-oxygen rocket in support of the Rocket Based Combined Cycle engine program. For these tests, the rocket engine has operated at simulated flight Mach numbers from 0 to 6.5.[380]

The DCSCTF and Test Cell 2 are currently in service.

Room C205, Mach 4 Blowdown Facility

The Mach 4 Blowdown Facility (M4BDF) is a horizontal blowdown tunnel with a 9- by 9-inch test section located on the second floor of Building 1221. It was built about 1976 as a tool for the preliminary evaluation of scramjet engine intake designs. Unlike the other STC tunnels, the M4BDF has no heater, nor does it support any combustion process. It is a simple tunnel that uses compressed air from Langley's central system and exhausts directly to the atmosphere through the northeast wall of the building. A muffler reduces its exhaust noise.

In the early days of scramjet research, the M4BDF stayed busy screening a wide variety of potential inlet configurations, but the adoption of integrated engine-airframe designs for aircraft such as those in NASA's Hyper-X Program have reduced those duties considerably during the last decade. The M4BDF is complete and serviceable, but now rarely used.[381]

Building 1247, Room B111, Arc-Heated Scramjet Test Facility

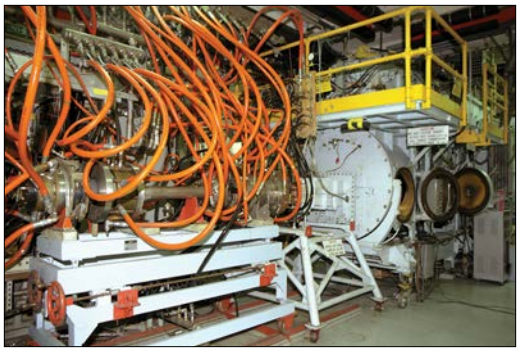
This 1989 photograph shows the Arc-Heated Scramjet Test Facility test section looking downstream. The exit of the nozzle, seen at the left, is approximately 11 inches by 11 inches, and the flow exhausts as a free jet into the test section. (Photo credit: NASA LRC-1989-B701_P-13628)

The fourth tunnel under direct HAPB control, the Arc-Heated Scramjet Test Facility (AHSTF), is located in the Hypersonic Facilities Complex. Originally named the 4-Foot Hypersonic Arc Tunnel, it was built in 1964 to support high-enthalpy hypersonic fluid mechanics research. In 1974, it was converted into a facility for testing complete scramjet models and renamed the Scramjet Test Facility. This name was later refined into Arc-Heated Scramjet Test Facility, to clearly distinguish it from the HAPB's combustion-heated scramjet tunnels in Building 1221. The conversion involved changes to the nozzle, model support hardware, and instrumentation, as well as the addition of a model fuel system, but its basic, arc-heated operation remained the same.

The AHSTF is in active service, testing scramjet models of up to approximately 8 by 10 inches in cross section at simulated flight speeds of Mach 4.7–8.0. Inlet air from a

Hyper-X Mach 7 DFX Engine installed in the Arc-Heated Scramjet Test Facility for testing in 1996. (Photo credit: NASA LRC-1997-B701_P-00836)

5,000-pound-per-square-inch bottle field passes through an electric arc, where it is heated to temperatures as high as 4,600°F, accelerated through the nozzle into the test section, and, as before, exhausted through an aftercooler to the 100-foot-diameter vacuum sphere. Engine fuel is gaseous hydrogen, with a 20-/80-percent silane/hydrogen mixture available to promote ignition. Run times are typically 10–60 seconds. During 2008, the AHSTF was reconfigured to run in a direct-connect mode, which simulates inlet conditions at the engine's combustor for tests involving fuel ignition and flame stability.[382]



The maze of cooling water connections to the Arc-Heated Scramjet Test Facility's arc heater and nozzle dominates this 1998 view, but the cylindrical test section with open access doors is also visible at right. (Photo credit: NASA LRC-1998-B701_P-01182)

15-INCH HIGH-TEMPERATURE TUNNEL

The 15-Inch High-Temperature Tunnel in Building 1251-A in the West Area, seen here in 1995. The modifications to the former Hypersonic Flow Apparatus reduced its speed from Mach 10 to Mach 6 but increased its inlet temperature. The original, closed test section is shown here. A second, open-jet test section removed from another tunnel was also used. Flow is left to right. (Photo credit: NASA LRC-1995-B701_P-04980)

SIGNIFICANCE

The 15-Inch High-Temperature Tunnel (15-Inch HTT), originally named the Hypersonic Flow Apparatus, was one of the first new wind tunnels built by the recently organized NASA to investigate the hypersonic flight regime. Modified for a lower speed, but a higher operating temperature, the tunnel hosted early work needed to fully relate compressibility, viscosity, real-gas effects, and thermal effects in hypersonic flight.

DESCRIPTION

The 15-Inch HTT is a blowdown tunnel that occupies the northeast corner of a portion of Building 1251 known as 1251-A in Langley's West Area. In appearance, it resembles a steel pipe with flanged connections. Near the center is the 14.57-inch-diameter test section, identified by its circular schlieren windows. It rests on a structural-steel stand, and a housing above it encloses the mechanism that actuates the angle-of-attack adjustment for the sting. A second, open-jet test section is also available. The sting includes a six-component, strain-gage balance to measure forces and moments. Ahead of the test section are a 1.25-megawatt electric heater, quick-acting control valves, a settling chamber, and the tunnel's axisymmetric nozzle. Downstream from the test section, the

tunnel features a diffuser with a variable second minimum. A long, tapered plug can be shifted longitudinally to vary the throat of the second minimum and optimize the location of the shock formed as the flow decelerates from supersonic to subsonic. The tunnel's centerline is approximately 5.5 feet above the floor.[383]

When in service, the 15-Inch HTT received air regulated by a reducing valve to 1,800 psi from a bottle rack outside the building. Langley's central utilities system supplied dried air to the bottles at a maximum pressure of 4,450 psi. When the control valves opened to allow flow through the tunnel, the air flowed through the electric resistance heater, which heated it to as much as 1,000°F, and through a settling chamber with screens to reduce turbulence before entering the nozzle. Exiting the diffuser, the flow passed through an aftercooler and a vacuum isolation control valve, and then into dual 54-foot-diameter steel vacuum spheres outside the building. These vacuum spheres, along with the pumps that evacuated them prior to test runs, were shared with the 31-Inch Mach 10 Tunnel.[384]

HISTORY

The 15-Inch HTT was originally constructed as the Hypersonic Flow Apparatus (HFA) in 1959, and its original location was Building 583 in Langley's East Area, the structure that had previously housed the NACA's Low-Turbulence Tunnel ("Ice Tunnel"). The HFA occupied the northwestern portion of the large room that comprised most of the building. It shared that room with the 26-Inch Transonic Blowdown Tunnel and the 20-Inch Variable Supersonic Tunnel. Although NASA inherited a number of hypersonic tunnels that had been built at Langley by the NACA, particularly those in the Gas Dynamics Laboratory, the increasing demand for hypersonic research facilities to support the budding space program justified additional capacity.

The HFA broke little, if any, new ground technologically, instead representing the use of the best available technology. Reports of test programs run in the HFA indicate that its primary use was in testing conceptual designs for atmospheric reentry vehicles, with an emphasis on their aerodynamic stability and control characteristics. Related projects investigated hypersonic flutter and boundary-layer separation. By the time this tunnel entered service, NASA had already decided to use conical, ballistic capsules for projects Mercury, Gemini, and Apollo, but work performed here, primarily by Lawrence Putnam and Cuyler Brooks, informed those who later designed the Space Shuttle orbiter.[385]

While it originally had been convenient and economical to erect the HFA in the existing Building 583, all of Langley's other hypersonic tunnels and operations were in the West Area, making support of the HFA difficult. Moving a wind tunnel, even a relatively small one like the HFA, is an expensive proposition, but NASA finally authorized the HFA's relocation to the West Area in the early 1970s, spending at least $425,000 between 1973 and 1977 to execute the move. One justification was the flow-visualization capability of the HFA, which was far superior to that of the 31-Inch Mach 10 Tunnel, whose side-mounted model-injection mechanism prevented good schlieren access. A

room adjacent to the one housing the 31-Inch Mach 10 Tunnel in Building 1251-A, part of the structure originally built for Langley's Unitary Plan Tunnel, became the HFA's new home. The availability of space and the ability to use the larger tunnel's air system made the move practical. Except for minor changes to the inlet and exhaust piping, the HFA was installed with no alterations to its configuration or capabilities.[386]

By the late 1970s, research work in the HFA had substantially declined, but President Reagan's call for a National Aero-Space Plane (NASP) in 1986 reinvigorated hypersonic research. Development of the plane, with its combined airframe and engine design, required a greater understanding of the characteristics of air at high speed and temperature. Researchers in Langley's Hypersonic Facilities Complex believed the HFA tunnel could help in a unique way if it were modified to reduce its speed and increase its operating temperature. The complex operated two similar Mach 6 tunnels with 20-inch test sections. One used air, while the other employed tetrafluoromethane (CF_4) as its test gas. Test data from the two were often compared to see how closely the CF_4 matched the real-gas characteristics of air at high temperature. They appeared to be close, but neither tunnel could generate Reynolds numbers high enough to be certain. The researchers needed a third tunnel, one that could match the speed using air, but generate higher Reynolds numbers. The 31-Inch Mach 10 Tunnel looked like a promising candidate, but it was solidly booked, so they decided to try the concept first in a revised HFA.[387]

Thus, the HFA underwent a modification program in the early 1990s, emerging as the 15-Inch High-Temperature Tunnel. The primary change was a nozzle redesign and re-machining that reduced its speed from Mach 10 to Mach 6 (prompting some people to call it the 15-Inch Mach 6 Tunnel). This change matched the speed of the other two tunnels, and the reduced flow, coupled with a new, more-efficient heater, allowed a higher inlet temperature. Provisions also were made to use a second, open-jet test section that formerly had been part of the Mach 6 CF_4 Tunnel. (That tunnel had received a new test section in 1988.) The larger chamber of the open-jet test section provided improved optical access for flow visualization, and its model injection system allowed adjustments in both pitch and yaw. The heater was changed from a 2-megawatt DC unit to a 1.25-megawatt AC heater. Though consuming less power, it provided inlet temperatures of more than 1,000°F. The 15-Inch HTT successfully produced the needed data. Although the comparison process of data from the three tunnels is rather esoteric and will not be discussed here, it produced sets of data that included the effects of compressibility, viscosity, real-gas, and thermal effects with a high level of confidence. The 15-Inch HTT achieved the desired results, but changes in bookings have allowed the 31-Inch Mach 10 Tunnel to host most of the more recent work in this area.[388]

Interest in hypersonic flight and vehicles has historically been cyclical, and the utilization of hypersonic tunnels has followed that cycle. Since the cancellation of the NASP Program in 1993, hypersonic test loads have been relatively low, and the facility was closed about 2000. Thus, the 15-Inch HTT remains intact, but unused.

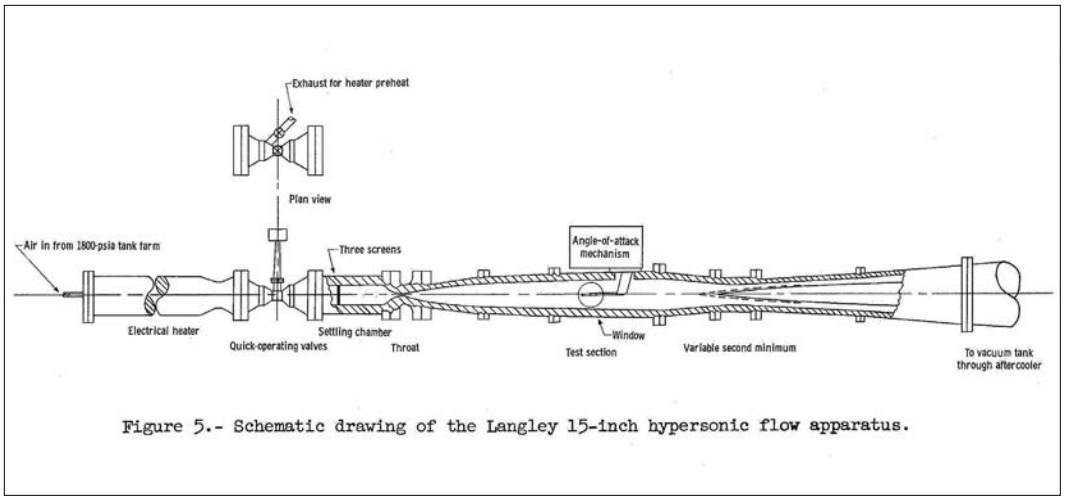
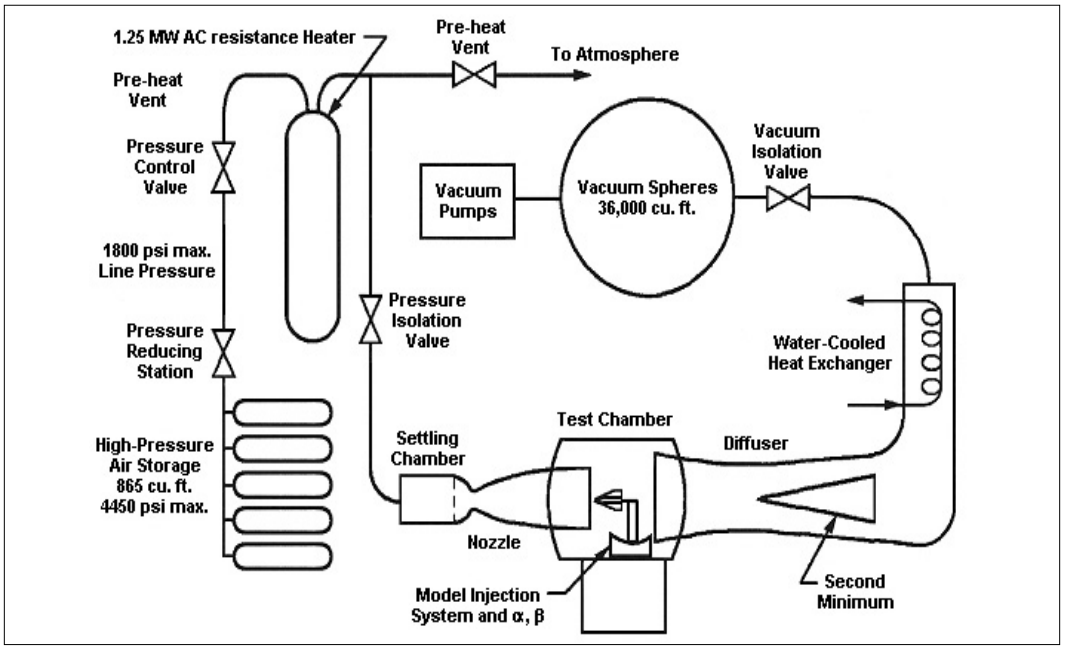


Figure 5.- Schematic drawing of the Langley 15-inch hypersonic flow apparatus.

This section drawing shows the major components of the Hypersonic Flow Apparatus as it was originally installed in Building 583 in the East Area. Except for the remachined nozzle and a relocation of the heater to outside the building, this configuration changed little during its conversion into the 15-Inch High-Temperature Tunnel. (Image credit: NASA TM X-733, Fig. 5)



This schematic drawing shows the major components and functional arrangement of the 15-Inch High-Temperature Tunnel. The open-jet test section is shown. The air system and dual 36,000-cubic-foot vacuum spheres are shared with the 31-Inch Mach 10 Tunnel. (Image credit: AIAA 92-3938, Fig. 1)

The 15-Inch High-Temperature Tunnel in Building 1251-A in 1991. (Photo credit: NASA LRC-1991-B701_P-12314)

Hardware for the 15-Inch High-Temperature Tunnel, seen here in 1995. (Photo credit: NASA LRC-1995-B701_P-04979)

28- BY 40-INCH BASIC AERODYNAMICS RESEARCH TUNNEL

The 28- by 40-Inch Basic Aerodynamics Research Tunnel as originally installed in Building 720-A in the East Area. Its fan section and exhaust are on the left in this 1985 image, with the test section and intake toward the right. (Photo credit: NASA LRC-1985-B701_P-03070)

SIGNIFICANCE

The 28- by 40-Inch Basic Aerodynamics Research Tunnel (BART) provides an economical venue for preliminary testing and development of a wide range of aeronautical design concepts, and for tests to verify the accuracy of computational fluid dynamics (CFD) software. The tunnel also serves as a platform for the development of wind-tunnel instrumentation and flow-visualization techniques.

DESCRIPTION

The BART, originally named the Vortex Physics Apparatus, is an open-circuit, subsonic wind tunnel designed and built by the Aerolab Corporation of Laurel, Maryland. It was designed to meet specifications written by researchers in Langley's Analytical Methods Branch (AMB) but constructed using many of the company's standard components. Aerolab's design was intentionally modular and adaptable to the additional modifications that would inevitably be made to any research device. Originally installed in Building 720-A in Langley's East Area, it has resided in West Area Building 1214, which was built specifically for it, since 1992.[389]

The 41-foot, 2-inch-long tunnel is mounted on a steel skid resting on six feet, making it movable as a single unit. This places the tunnel's centerline 6 feet, 9 inches above the floor. The Buffalo Forge axial-flow fan adds another 4 feet, 4 inches, but it is mounted on a separate steel base and connected to the tunnel's diffuser by a flexible connection to minimize vibration transfer to the tunnel. The fan is turned by a 125-horsepower, variable-speed, AC motor controlled by a frequency-regulator with manual controls mounted next to the test section. The motor is mounted on the fan base and drives the fan via a magnetic clutch and V-belts. The combination delivers a maximum speed of 126 mph.

The BART has an 8-foot, 10-inch by 10-foot, 6-inch inlet, which contains a honeycomb and four 20-mesh stainless steel screens for smoothing the flow. An 11:1 contraction leads to the test section, which measures 28 inches by 40 inches and is 10 feet long, twice Aerolab's usual length for a tunnel this size. It is divided into two bays, each consisting of a square-steel-tube frame and wall panels that can be replaced easily with test-specific panels. As delivered, the sidewalls were acrylic glass, but the BART technicians normally use optically clear glass to aid various photographic techniques. The top and bottom walls may be clear or solid, and any wall can be fitted with a model mount. Original equipment included pitot probes at the contraction throat connected to an inclined manometer for airspeed indication. The 16-foot, 6-inch diffuser transitions from rectangular to circular to match the fan housing.

Since the BART performs several types of tests, its instrumentation varies to suit each program, and its data acquisition system has received several modernizations over the years. The most commonly used instrumentation includes pressure-survey probes and optical devices for flow-field measurement and visualization.

HISTORY

The history of the BART actually begins about two decades before its purchase. Realizing the potential of an emerging technology, NASA began serious developmental work on CFD techniques shortly after the agency's founding. In time, the growing need to experimentally validate CFD equations led NASA to purchase a wind tunnel designed for that purpose.

During the late 1950s, a group of Atomic Energy Commission scientists and mathematicians at Los Alamos, New Mexico, began introducing a number of numerical methods that could be used in electronic computers to generate partial solutions to fluid mechanics problems in reasonable times. Numerical solutions to these problems had been theoretically possible using equations developed by Claude Navier and George Stokes in the 1800s, but the complex, nonlinear equations literally took someone weeks, or even months, to manually solve a relatively simple problem. By 1960, computers had begun to make the huge volume of calculations practical and much less prone to error, and within 20 years, commercial CFD software started to become available.[390]

Researchers at NASA and elsewhere recognized that aerodynamics would be a major CFD application, but numerous problems needed resolution. Aerodynamics involves very complex flows around multi-curved surfaces, and the CFD software, or code, quickly became a composite of subroutines that were complex in and of themselves. Adding to that the fact that every airplane design was unique made it virtually impossible to know if the CFD predictions were accurate. By the mid-1980s, CFD code validation had become a major issue, and standards for it were being developed by NASA and others. At Langley, AMB researchers concluded that a simple, commercially available wind tunnel with a state-of-the-art data acquisition system would give them the tool they needed to validate and improve CFD code.

Accordingly, AMB people contacted Aerolab Corporation in Laurel, Maryland, a company that built such tunnels for industry, laboratories, and schools, about building what they first called a "Vortex Physics Apparatus." Aerolab replied with a design based on a standard model, but with changes to meet AMB's specifications, including a longer test section and specific honeycomb and screen patterns. The tunnel that would eventually be renamed BART was delivered to Langley in November 1984.[391]

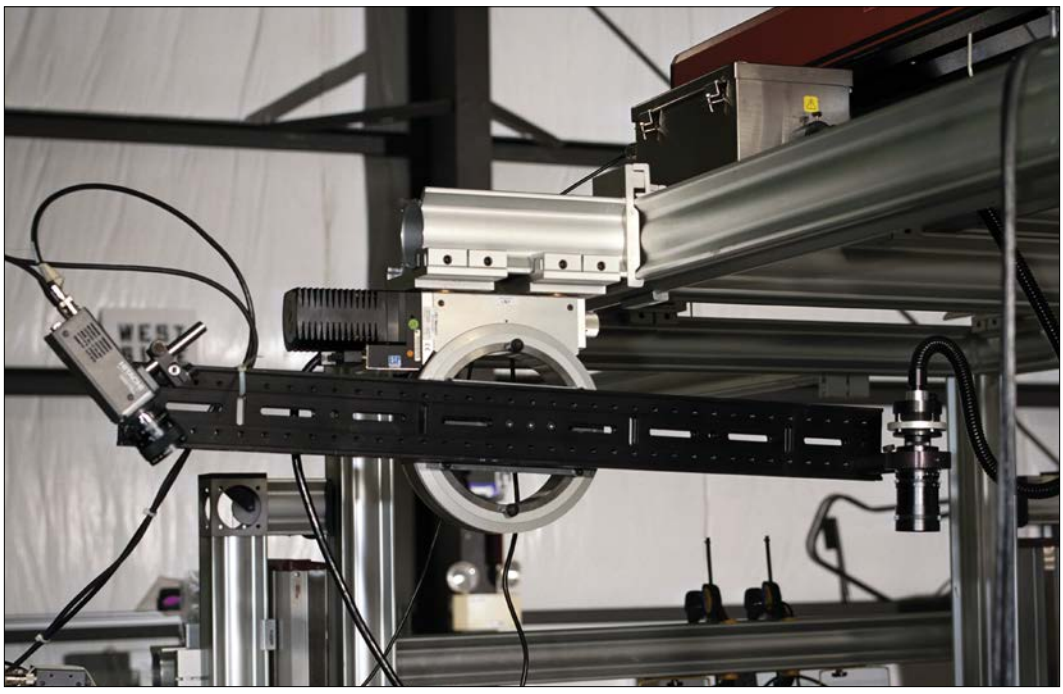
The tunnel was skid-mounted, so it could be placed anywhere there was sufficient room. The location selected was Building 720-A in Langley's East Area. While less than convenient for the AMB staff, this annex to one of Langley's deactivated seaplane towing tanks had been vacated by the free-flight and spin tunnels model shop and was available. Once installed, the BART was calibrated by the AMB staff and placed in service running CFD code-validation tests.[392]

An important component of validation involved flow visualization to determine if actual flows matched those drawn by the CFD code. Langley researchers David Rhodes, John Franke, Stephen Jones, and Bradley Leighty tackled the problem, and they developed a technique that used a laser and mirrored galvanometers to establish thin "sheets" of light that intersected the model. Tiny (0.8-micrometer) polystyrene spheres injected into the flow field in a water-alcohol vehicle reflect the light when passing through the sheet of light. By using two collimated beams, they established a fringe pattern of known spacing. The particles reflected light only when they crossed fringes, which yielded the particles' local speeds. The technique, known as laser doppler velocimetry (LDV), is now widely used. A related technique called particle-imaging velocimetry (PIV) uses multiple exposures to generate two-dimensional vector flow fields. Continuing research using the BART has developed increasingly sophisticated refinements of these techniques.[393]

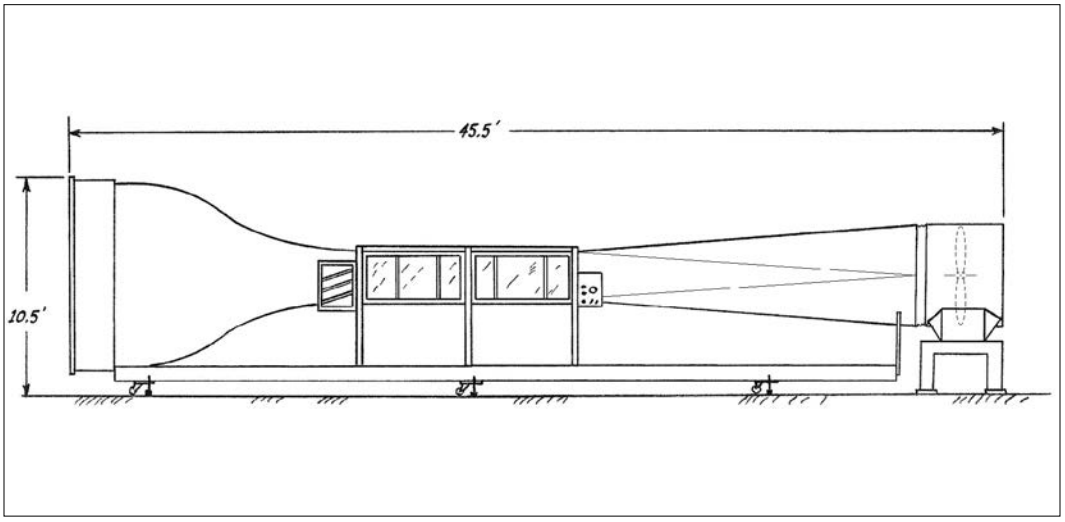
During the 1980s, NASA looked seriously at reducing its costs by eliminating facilities that were closed or obsolete. One of these was Towing Tank Number 2 (Building 720), which had been deactivated in the 1960s, except for some wake vortex investigations that continued into the 1970s in the 720-B portion of the structure. Annex 720-A had been considered a temporary home for the BART, and demolishing the building meant that the issue of a permanent home had to be faced. Several existing buildings in both the East and West Areas were considered, but the ultimate decision was to construct a

new building specifically for the BART. Building 1214, a manufactured metal building, opened in the West Area in 1992, and the BART was quickly relocated to it. The tunnel occupies one large room and approximately one-half of the building's area, while offices, data acquisition equipment, and other support rooms complete the interior.[394]

The BART's mission has changed little since its relocation, and it continues to host programs intended to empirically validate elements of CFD code, along with programs that develop testing, measurement, and flow visualization techniques. But the BART has also proved to be a convenient, economical venue for a variety of aerodynamic test programs, particularly unusual ones such as biologically inspired micro aircraft. With its excellent flow visualization capability, it is very useful for evaluating the complex, often unsteady flows around such things as extended landing gears and wings with high-lift devices deployed. Recently, these studies have extrapolated unsteady flow turbulence into characteristics related to the generation of audible noise. Thus, the BART, one of Langley's most basic wind tunnels, continues in active service with some of the center's most sophisticated measurement systems and programs.[395]

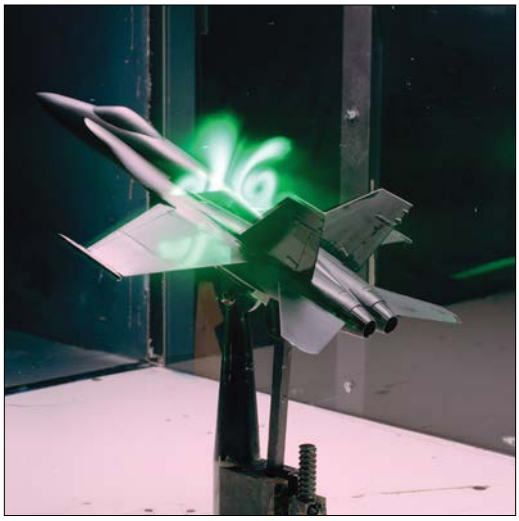


Variation of baseline configuration and the Projection Moiré Interferometry setup for a test of the Micro Air Vehicle in the Basic Aerodynamics Research Tunnel in 2001. (Photo credit: NASA LRC-2001-B701_P-01274)

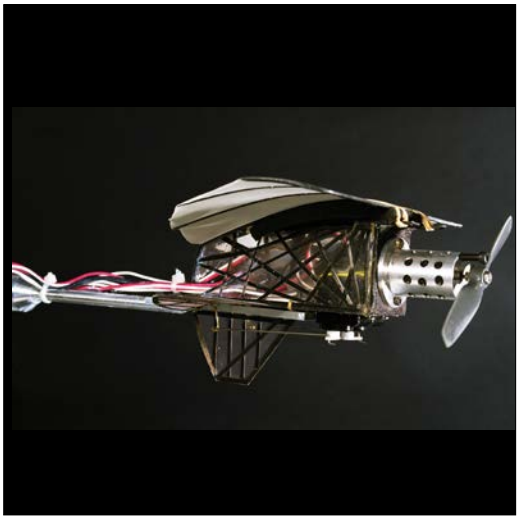


The Basic Aerodynamics Research Tunnel's overall arrangement is apparent in this elevation drawing. Its glass-walled test section is relatively long for a tunnel of this size. The 125-horsepower motor is mounted on the opposite side of the fan at the right end. The box with three inclined tubes is an air-speed manometer fitted as original equipment. Flow is left to right. (Image credit: AIAA-2006-0069, Fig. 9)

The Basic Aerodynamics Research Tunnel's honeycomb intake dominates this 2014 view of the tunnel after its move to Building 1214 in Langley's West Area. (Photo credit: NASA LRC-2014-B701_P-01145)



These four examples show just a few of the many models and concepts studied in the Basic Aerodynamics Research Tunnel: (top left) laser doppler velocimetry and imaging, looking at a single position around an F/A-18; (top right) laser doppler velocimetry observing three positions simultaneously around an F-16XL; (bottom left) a biologically inspired micro air vehicle; and (bottom right) a Mars Tumbleweed Rover concept. (Photo credits: NASA LRC-1991-B701_P-14435, NASA LRC-1992-B701_P-11001, NASA LRC-2001-B701_P-01267, and NASA LRC-2003-B701_P-01060)



NATIONAL TRANSONIC FACILITY

This 2000 aerial view of the National Transonic Facility shows the tunnel with its drive motor and test section enclosures in the center, the nitrogen run tank at the upper left, and the nitrogen storage tank at the lower right. The air mode cooling tower and nitrogen vent stack are also visible. (Photo credit: NASA LRC-2000-B701_P-00742)

SIGNIFICANCE

The National Transonic Facility (NTF) is NASA's newest and most advanced wind tunnel for testing in the transonic flight regime. It utilizes a combination of pressure and very low temperature to produce test conditions with Reynolds numbers equivalent to full-scale flight in the vicinity of Mach 1. Liquid nitrogen is injected and vaporized to generate cryogenic conditions, but the tunnel can also operate using air as the test gas.

DESCRIPTION

The NTF, Building 1236 in Langley's West Area, is a closed-circuit, welded-stainless-steel-shell wind tunnel designed to operate between 14.7 and 130 psia pressure and at cryogenic (very low) temperatures to produce Reynolds numbers equivalent to those of full-scale transonic flight. The use of temperatures as low as –250°F decreases the viscosity term of the Reynolds number formula. This complements increases in the density term from higher pressures to achieve Reynolds numbers substantially higher than can practically be achieved through pressure alone. For tests requiring lower Reynolds numbers, the NTF can operate using air as the test gas.

The tunnel alone measures approximately 221 by 70 feet in plan, although buildings for the drive motor, nitrogen injection equipment, model preparation, office, and control

room areas occupy additional space. The NTF complex also includes a cooling tower, two large liquid nitrogen storage tanks, a building for nitrogen handling equipment, and a vent stack to remove pressurized nitrogen gas and air from the tunnel. A liquid nitrogen production plant just west of the NTF opened in 2008.[396]

The NTF's 8.2-foot-square test section incorporates a design similar to the one developed for the 8-Foot TPT. It is equipped with six slots each in the floor and ceiling for transonic operation and has small filets in the corners to help smooth airflow through the section. The sidewalls each have two additional slots, but these are normally closed. Full-span models can be mounted on a sting with remotely controllable pitch and roll adjustments. A circular-arc sector adjusts pitch over a range from –11.5 to 19.0 degrees, and 360 degrees of sting roll is available. Six-component, strain-gage balances are normally used to mount the model to the sting, and a variety of pressure and temperature measurements can also be taken. Sidewall mountings support tests of semi-span models as well, with similar pitch (angle-of-attack) adjustability.[397]

As with other slotted-wall tunnels, the NTF's test section is enclosed in a 27-foot-diameter plenum that directs airflow through the slots and serves as the test section's pressure vessel. Two movable rectangular tubes roll in horizontally from opposite sides to provide personnel and model access level with the test section's floor. With these tubes inserted and two gate valves closed to seal the plenum from the rest of the tunnel, the cold nitrogen gas within the plenum and tubes is heated and purged with air to provide a safe environment for the technicians without having to purge the entire tunnel. For test runs, these tubes are retracted, and their pressure doors are closed to seal the plenum from its surrounding test chamber, after which the plenum is recharged with nitrogen and the gate valves are opened.[398]

The high-speed diffuser extends through the first corner and into the second leg. Its first section transitions from square to circular to suit the bulk of the tunnel's circuit. All four corners are fitted with turning vanes. Four sets of injectors in the second leg spray liquid nitrogen at –250°F into the tunnel immediately ahead of the fan's inlet nacelle during cryogenic operation to reduce the tunnel's operating temperature to as low as –320°F.[399] No nitrogen is injected during air operation, where operating temperatures as high as 120°F are common.[400]

The fan inlet nacelle extends around and through the second corner to the 25-blade fan in the second leg. The fiberglass-bladed fan is powered by a 135,000-horsepower, variable-speed synchronous motor that is controlled by a load commutated inverter (LCI). This arrangement replaced the original drive, which employed two 30,000-horsepower induction motors salvaged from the 4-Foot Supersonic Pressure Tunnel connected through a two-speed gearbox to a 66,000-horsepower synchronous motor, in 1998. Remotely adjustable inlet vanes ahead of the fan assist in controlling the NTF's speed, which ranges from Mach 0.1 to 1.2. Stator vanes on a tapered downstream nacelle minimize swirl.[401]

The diameters of the second and third legs of the NTF are proportionally smaller than in most modern tunnels to minimize the volume of test gas needed and to reduce the surface area of the tunnel's shell and, thus, its heat gain from the environment. The circuit is internally insulated with 6–7.5 inches of rigid, closed-cell polyurethane foam secured to the shell. An acoustic layer of fiberglass is inside that, and both are protected by an aluminum inner liner. The inner liner, made up of flat plates, gives the tunnel a 24-sided polygon cross section. Additional acoustic attenuation panels cover portions of the nacelles.[402]

The tunnel's third leg has two extraction ports where an exhaust system removes the amount of test gas necessary to maintain the desired pressure in the tunnel. Little extraction is needed in the air mode, but an amount of gas equivalent to the liquid nitrogen injected, approximately 1,000 pounds per second, must continually be removed during cryogenic-mode operation. This is accomplished by an ejector-type vent stack. Fans blow air through a nozzle at the base of the stack to create a draft on the extraction ports, mix this air with nitrogen from the tunnel, and exhaust the combined flow vertically into the atmosphere. Control valves regulate the flow to control the tunnel's pressure, and a muffler vents the exhaust flow into the stack. A natural gas burner warms the cold gas flow when necessary to prevent condensation and fog in the area during periods of high humidity.[403]

After the fourth corner, a wide-angle diffuser quickly enlarges the tunnel's cross section into its settling chamber, which contains a cooling coil (used during air mode operation) and four anti-turbulence screens. The tunnel reaches its greatest diameter, 36 feet, in the settling chamber. A 14.95:1 contraction that also transitions from circular to square leads to the test section and completes the circuit. As with the high-speed diffuser, a portion of the contraction cone retracts to allow a gate valve to isolate the test section and plenum when desired.[404]

HISTORY

Since the dawn of the jet age in the late 1940s, the preponderance of military and civilian flight has been in the transonic regime, ranging from about Mach 0.7 to 1.2, with the bulk of that below Mach 1. The transonic regime includes localized regions of both subsonic and supersonic flows around an airplane, making it far more complicated to understand and analyze than the slower and faster speed ranges. As discussed in the 8-Foot HST section, test-section choking at Mach 1—slower with a model in the test section—prevented successful wind tunnel operation until Langley's Ray Wright installed a slotted-wall test section in 1948. This quickly became the key element of transonic tunnel design, but it could not address other issues critical to transonic research. At Langley and elsewhere, several transonic tunnels were constructed during the 1950s to support the rapid conversion to jet aircraft, and some of them were pressurized to generate higher Reynolds numbers, a technique dating back to Langley's VDT of 1922. But for jet speeds, the pressurization required to duplicate in-flight Reynolds

numbers was too high to be practical for a large tunnel, so engineers began to investigate whether other terms of Reynolds's formula could be varied as well. Work done by British researcher R. Smelt in 1945 pointed to temperature reduction as a possible solution, though the technology to produce the cryogenic (very low) temperatures needed was impractical before the mid-1960s. Langley researchers started a serious study of possible alternatives in 1966, and this led to experiments in 1971 with liquid nitrogen at –321°F as a means to chill wind tunnels. Their work culminated in the construction and successful start-up of the 0.3-Meter TCT in 1973. The TCT quickly validated its engineers' design predictions, and it generated unprecedented Reynolds numbers—up to 100 million per foot. It was, however, too small to be suitable for three-dimensional testing of complete aircraft models.[405]

The next step was to design and build a cryogenic tunnel large enough to support three-dimensional testing of reasonably sized models at comparable Reynolds numbers. This proved to be a far more complex challenge than simply scaling up the TCT. As the test section's size increased, so did the tunnel's total volume, surface area, and power requirement, along with greater risks from other potential problems, such as media contamination, model access, instrumentation, and noise. The engineers had to make a host of trade-off decisions to develop a design that would deliver the desired test conditions at reasonable construction and operating costs. These trade-offs soon indicated an optimum test section size of about 8 feet square.

During the same period, the Air Force countered that such a tunnel was unnecessary and that the service could generate the needed data more economically using an impulse tunnel design known as a Ludwieg tube if it was operated at high pressure. The debate was settled in 1974 when Congress approved funds for what was named the National Transonic Facility. It was to be the nation's primary facility for both military and civilian transonic research. With the NTF costing about $85 million, Congress had no intention of building a separate Air Force facility.[406]

To help keep the NTF's cost as low as possible, Langley engineers proposed to demolish the 4- by 4-Foot Supersonic Tunnel and construct the new NTF on its site. This would allow reuse of the old tunnel's drive motors, cooling tower, and portions of its buildings. Thus, the NTF is identified as Building Number 1236, the same number as its predecessor.[407]

Engineers designed the NTF to operate in two modes. Many tests could be run in air at nominal temperatures using pressurization alone to increase Reynolds number. Such tests would be considerably cheaper than those in the cryogenic mode. In air mode, the tunnel would operate like other closed-circuit tunnels and use cooling coils just before the settling chamber to remove the heat generated by the drive. Circulating water would convey the heat to the existing cooling tower.

The tunnel would operate very differently in cryogenic mode. Liquid nitrogen would be continuously injected into the tunnel, where the lower pressure would cause it to evaporate. This phase change would absorb heat from the tunnel's gaseous nitrogen

atmosphere, and it could reduce the temperature down to –320°F. With nitrogen being continuously added, a gaseous nitrogen vent system would be needed to continuously extract enough of the gas to maintain the desired pressure. This system would use an air-driven ejector to mix the extracted nitrogen with air and exhaust the gas to the atmosphere, with regulating valves in the vent system to maintain the tunnel's static pressure at its setpoint. Achieving the desired conditions would require that approximately 1,000 pounds of nitrogen pass into and out of the tunnel per second.[408]

After eight years of design and construction, the NTF was finally completed in September 1982. Operators began an extensive series of checkout and calibration runs the following month. The checkout process took about 18 months, during which numerous adjustments and alterations were made to solve various problems. Considerable effort went into the installation of model access equipment and housings during this time as well. Three months of preliminary calibration runs began in May 1984, and the tunnel became operational in August. As operations began, engineers and technicians performed more extensive calibration work in both air and cryogenic modes, and the first model test program began in December. Expecting the unexpected from a complex new facility, particularly one of a type for which there was very little operating experience, the NTF team decided to operate for at least three years in a combined "checkout-and-test" program. This proved to be wise, as operating in actual cryogenic testing conditions quickly exposed any weaknesses in the tunnel's machinery and instrumentation in the harsh environment.[409]

Cryogenic operation soon revealed two unanticipated problems. The first was frost formation on models. A study proved that the frost was water, but the source was not obvious. The culprit was found to be the internal, closed-cell-foam insulation, which had a low water content that flashed from it at the NTF's operating conditions. This caused no problems at normal temperatures, but at –70°F, only about 0.2 pounds of water will saturate all of the gas in the tunnel—only a thousandth of the amount needed at 70°F. The initial solution was to "dry" the tunnel by keeping the nitrogen in the tunnel at 150°F for several hours before starting a test. Periodic purges removed the moisture, and the continuous venting during operation kept the humidity low enough to have negligible effects on test data. Maintaining a dry environment in the tunnel at all times, whether operating or not, to minimize water absorption by the foam, proved to be a practical long-term solution. Since the TCT has *external* insulation, this situation had not previously occurred there.[410]

Significant model vibration that worsened as the tunnel's temperature decreased presented another challenge. The NTF's hydraulically actuated sting is mounted on an arc sector that passes through guides in the test section's floor and ceiling. It also has a streamlined fairing on its trailing edge that is fixed to the tunnel. Through a combination of analysis and experimentation, the engineers identified two causes: improper clearance at the arc sector guide bearing pads, and unsteady airflow leaving the fairing. More-careful adjustment of the pads and the addition of small vortex generators on the

fairing reduced the vibration to manageable levels. As with the water contamination, this problem had not appeared in the TCT because of model-mount design differences.[411]

In spite of these and other difficulties, the NTF generally performed well and met its design goals. Most importantly, it achieved a Reynolds number of 120 million at Mach 1 with steady flow characteristics. The first model tests clearly demonstrated "significant Reynolds number effects," thus validating the cryogenic design concept.[412]

As engineers' and researchers' confidence level in the NTF grew and the number and severity of operating problems decreased, the facility moved into an operating mode, though development projects would continue to enhance the tunnel's capabilities. As anticipated, most of the test projects involved sting-mounted models, but some utilized the sidewall mounting hardware.

During a run on the afternoon 18 January 1989, a retaining ring holding insulation around the fan's drive shaft failed. Pieces of the broken ring were thrown outward, where they impacted portions of the aerodynamic fairing on the upstream side of the fan, causing five panels to dislodge and strike the fan, damaging all 25 blades beyond repair. The shaft insulation had been installed to reduce thermal stresses between the fan disk and shaft. An extensive analysis reconstructed the accident scenario, and it indicated the retaining rings were very highly stressed. A thermal analysis indicated that the stresses in the shaft would be well within its capabilities without the insulation, so the engineers removed it, along with the troublesome retaining rings. New fiberglass fan blades were required, but two different types of fiberglass fabric had to be used in their construction, so testing was done to be sure the two fabrics were compatible. Repairs to the NTF took about a year to complete.[413]

Since returning to service, the NTF has received numerous enhancements to improve the facility's capability, reliability, and productivity. One of these, the Model Protection and Shut-down System (MPSS) installed in 1994, continually monitors dynamic loads on models under test and automatically stops the run should these loads reach levels that threaten to damage the model. An additional benefit of the MPSS is its ability to furnish analytical data about model and support vibrations.[414]

During 1997–98, engineers made a number of improvements to enhance the NTF's productivity, including a new drive motor, expanded liquid nitrogen storage, control enhancements, a faster data system, and an improved model changeout system. A single, 135,000-horsepower, variable-speed motor replaced the three-motor, 126,000-horsepower drive originally installed. It is a synchronous motor with an adjustable-frequency drive. In addition to more power, the new arrangement is far simpler, is more reliable, and maintains its set speed—up to 600 revolutions per minute—more precisely than its predecessor. The motor's builder, ABB Industrial Systems, Incorporated, claimed at the time that this was the world's most powerful adjustable-speed drive system using a single motor.[415]

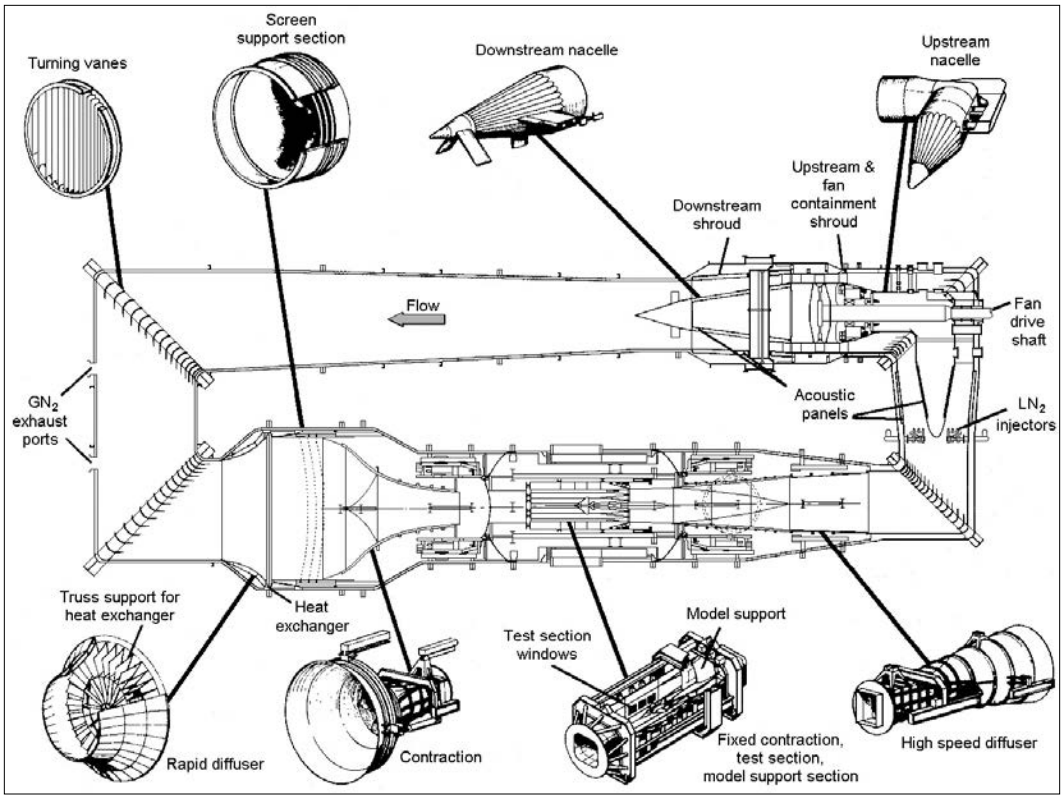
Operational experience had shown the original 250,000-gallon liquid nitrogen tank to be inadequate. Filled from a nearby commercial liquid nitrogen plant at 250

gallons per minute, it could not keep up with the test schedule. A new, 900,000-gallon tank was installed at the tunnel's east end with connections to both the liquid nitrogen plant and the original tank, which has subsequently served as a run tank. This doubled the NTF's continuous run time to 3 hours. Exhausting gaseous nitrogen had proven to be a problem as well, especially during periods of high humidity when the exhausting plume of cold vapor tended to form a cloud on the ground rather than disperse and evaporate. The severe limitation this placed on visibility in the area forced operations to cease until weather conditions improved—a major frustration for operators and customers. The solution was a natural gas burner in the vent stack that maintains an exhaust temperature of 750°F.[416]

Another modification program in 2002 improved the NTF's performance using air by completely rebuilding the cooling system. Engineers made numerous changes to minimize problems due to corrosion, debris, and thermal cycling between air and nitrogen operations. This project also replaced the earlier balance, known as the NTF-113 Balance, with a more-robust NTF-116A design and a stiffer sting to reduce dynamic load problems. During 2008, Langley built its own plant to produce liquid nitrogen west of the NTF and subsequently discontinued commercial purchases of nitrogen.[417]

As with most modern tunnels, the NTF has supported a variety of aircraft development and pure research projects over the years. Aircraft tests have ranged from high- and low-speed studies of existing and proposed civilian transports to the validation of computational fluid dynamics (CFD) analyses for proposed designs. Some of these have focused on performance at high angles of attack. Research projects have been instrumental in the development of testing techniques, such as optical methods for measuring wing twist and the use of pressure-sensitive paint in cryogenic conditions. Other projects have compared NTF data from those produced by other well-known facilities and flight tests to minimize uncertainty and better define the contributions from cryogenic operation.[418]

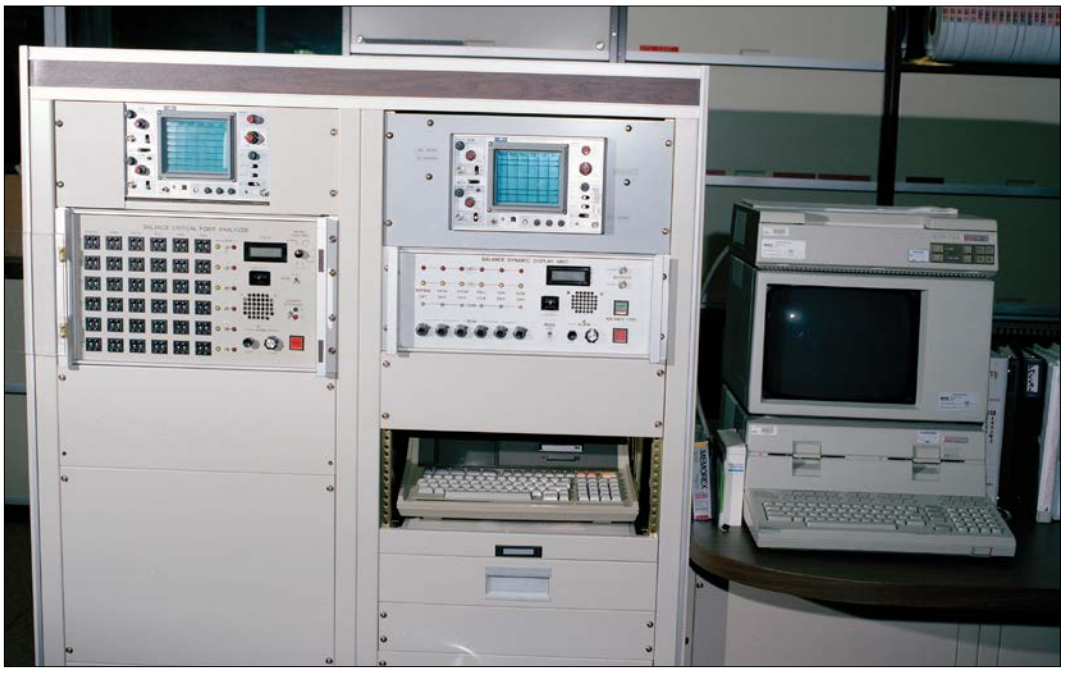
Although complex and relatively expensive to operate, the NTF is one of three tunnels at Langley (along with the Transonic Dynamics Tunnel and the 8-Foot High-Temperature Tunnel) that are considered sufficiently vital and unique to warrant inclusion in the National Resource Protection Program. With its unique ability to operate almost continuously at conditions accurately simulating full-scale flight from low speeds into the transonic regime, the NTF remains in active service.[419]



The complexity of the National Transonic Facility is apparent in this drawing, even though it does not show the drive motor, nitrogen-handling equipment, vent stack, or test section access tubes. (Image credit: NASA LRC-1983-B701_P-02910)

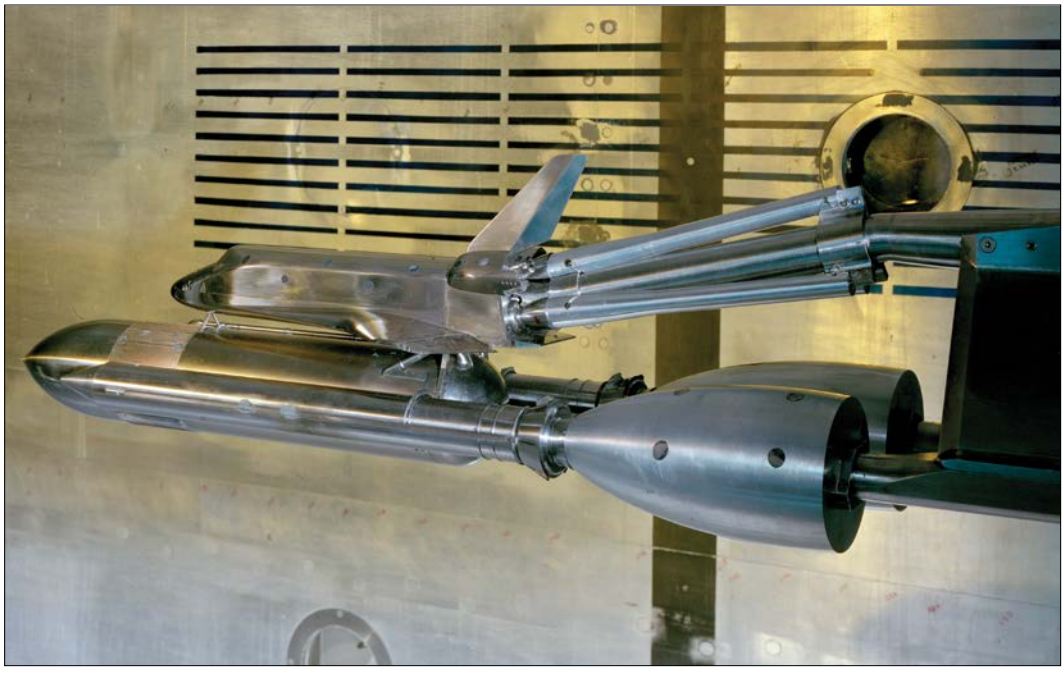
Operators manage all aspects of National Transonic Facility operations from this control room, seen here in 1990. Adjacent areas provide space for customers' equipment and test personnel. (Photo credit: NASA LRC-1990-B701_P-14509)

This 1985 photograph shows Pathfinder model in the access tube that allow engineers and technicians to service installed models without purging all the National Transonic Facility's nitrogen or raising its temperature. Two of these insulated, retractable access tubes meet at the center of the test section to surround the model and provide a habitable work environment. (Photo credit: NASA LRC-1985-B701_P-13516)



National Transonic Facility operators used this control equipment, seen here in 1988, to manage the balance system. (Photo credit: NASA LRC-1988-B701_P-13575)

Liquid nitrogen injected through these nozzles, seen here in 1983, rapidly evaporates to cool the National Transonic Facility to operating temperatures of about –250°F. (Photo credit: NASA LRC-1983-B701_P-10552)



A sting-mounted Space Shuttle stack installed in the National Transonic Facility for ascent tests in 1985. The bulbous extensions simulate the engine exhaust plumes. (Photo credit: NASA LRC-1985-B701_P-01774)

A semi-span B-777 installed for tests in the National Transonic Facility in 2003 with its main landing gear and flaps extended. Note the vertical arc sector and sting mount (not used for sidewall-mounted tests) behind the model's wing. (Photo credit: NASA LRC-2003-B701_P-01570)

Like the Full-Scale Tunnel in 1950, the National Transonic Facility has been used to evaluate submarine hull designs for the Navy. The inverted position minimized adverse effects from the support stand. (Photo credit: NASA LRC-1986-B701_P-09574)

PREFLIGHT JET FACILITY AT THE WALLOPS ISLAND STATION

Looking west at the Preflight Jet Facility on Wallops Island in 1959. In the background are the rectangular test house and air storage spheres. The air compressor and dryer house are in front on the right. (Photo credit: NASA LRC-1959-B701_P-02750)

SIGNIFICANCE

The Preflight Jet Facility at the Wallops Island Station was one of the NACA's earliest facilities for supersonic testing. As NACA and NASA engineer Joseph Shortal stated, "The Preflight Jet Facility was the first true-temperature, sea-level pressure, supersonic-speed facility known in this country."[420] Built primarily to test ramjet engines prior to flight, the Preflight Jet Facility proved to be a versatile wind tunnel that was easy to adapt to other uses, and it hosted a wide variety of the NACA's early supersonic and high-temperature test programs.

DESCRIPTION

The Preflight Jet Facility was one of several structures dotted along the Atlantic shore of Wallops Island, Virginia. Most of these supported the launching of small, solid-fueled rockets used for scientific and engineering development work, but the Preflight Jet Facility sat farther back from the shore and looked quite different from the other launch, support, and administrative buildings. Approaching it, one first saw two large spherical tanks and a building with roll-up doors for sides. Closer inspection revealed this building to have a second, shorter portion of masonry construction, and two smaller concrete buildings a short distance away. The entire complex occupied a plot approximately 100 by 165 feet in size.

The Preflight Jet itself occupied the largest building, with all but its test section in the low-rise portion. Its design harked back to the world's first wind tunnel, built by Francis Wenham in 1871, in that it basically provided a jet of air into an open space, with test objects placed just outside the nozzle's exit. The facility initially featured two nozzles, or "jets," known as the A, or Main, Jet, and a second B Jet. Interchangeable nozzles allowed speeds of up to Mach 2.25. The test house's doors were rolled up during test runs, making it into an open shed. This allowed safe viewing of the tests from a blockhouse-like observation house about 25 feet away. This 20- by 20-foot building had a raised portion facing the test house with periscope windows. When testing a new, highly energetic device like a ramjet, explosive failures were a significant risk, so the observation house and roll-up doors minimized the exposure to personnel and facility damage should such a failure occur.

The low-rise portion of the main building housed an air heater and circulation system to heat air flowing to either jet, as well as a quick-acting "rotovalve" in a pipe connected to the two steel spheres just outside to the north. Each sphere measured 28 feet, 10.75 inches in diameter and could store 12,500 cubic feet of air. About 35 feet east of the spheres, a separate 30- by 38-foot masonry building housed an air compressor (two compressors after 1954) and a duplex, activated-alumina dryer to furnish the dry, compressed air.[421]

The facility received a third jet, the C Jet, intended for high-altitude simulations, in 1953, and the B Jet was converted into a high-temperature jet with the addition of an ethylene burner, including a fuel storage and supply system, in 1956. In 1955, a hydraulically operated valve was installed between the heater and jets to eliminate the need for bolting a blanking plate over the main jet when one of the auxiliary jets was used.

HISTORY

The initial development of jet engines during World War II promised a post-war era of flight at much higher speeds than any propeller-driven plane could reach, and engineers at the NACA realized that they had no facilities to investigate speeds above about Mach 0.85. Flight testing appeared to be the only available avenue for the foreseeable future, but it would have to be done using models, since no crewed aircraft could yet reach the desired speeds, much less do so safely and at reasonable cost.

To further explore the realm of high-speed flight, the NACA authorized Langley to establish a Pilotless Aircraft Research Division (PARD). PARD would conduct flight experiments using models dropped from carrier aircraft or launched with simple rockets. These tests would have to be over the ocean for safety reasons, with the models lost into the sea at the end of each flight. Telemetry and radar systems recently developed by Langley's Instrument Research Division (IRD) made it possible to collect much of the data measured in wind tunnels from the models during their brief flights. Langley Field could host the drop tests, but rocket launches were out of the question in a developed area, and security would be easier in a remote location as well.

Wallops Island, a barren island just off the Eastern Shore of the Delmarva Peninsula, had the necessary attributes, and Langley began the difficult task of developing the site, initially known as the Pilotless Aircraft Research Station, in 1945. Wallops launched its first rocket from a temporary launch stand that same year.

Ramjets also held considerable interest for engineers at the time, as they offered great promise for supersonic propulsion due to their power and simplicity. A ramjet engine has no moving parts, but it can operate only at speeds high enough for shock compression to occur just inside its inlet. Thus, a ramjet-powered aircraft or missile has to be boosted to its ignition speed by some other means—usually a rocket—before the ramjet can be ignited. In 1944, both the Army and Navy asked Langley to investigate their use in air-to-air and ground-to-ground missiles. This investigation needed a new ground-test facility as well as a launch platform for flight tests, so Langley engineers requested a supplemental appropriation to build them as part of the Wallops Island project.[422]

For the wind tunnel, Langley engineers originally proposed a continuous-flow jet using two engine-driven blowers, but PARD Chief Robert Gilruth felt that would be inadequate. Additional analysis of the problem led to a blow-down design using compressed and heated air. While it would be an intermittently operating facility, it could produce conditions much closer to those needed. The Pittsburgh–Des Moines Steel Company (PDM) won the bid to supply the Preflight Jet components, while general contractor Doyle & Russell, Incorporated, received the contract to build the supporting structures. PDM Chief Engineer J. O. Jackson took a personal interest in the unique facility, and he proposed that the Preflight Jet should store 50,000 cubic feet of air at about 200 psi, then release it to the jet nozzle through a preheated heat exchanger. PARD engineer Paul Hill suggested using a heat exchanger made up of tubes instead of the more-commonly used pebbles. PDM's design was accepted, but the air storage had to be cut in half to stay within the limited budget.[423]

Begun in June 1946, construction took almost two years, but the Preflight Jet was ready for calibration runs in April 1948. These runs revealed some heat exchanger and control problems that delayed full operation until early 1949. A third problem involving rust and scale flakes in the air appeared later. This resulted from the use of carbon steel instead of expensive stainless steel. The problem never disappeared entirely, but keeping the heater hot and sealed off from atmospheric moisture kept the airstream contaminants to an acceptable level.[424]

The facility opened with a main A Jet and a smaller auxiliary B Jet, but space was provided for a future, third nozzle. The B Jet, which used interchangeable nozzles measuring between 5 and 8 inches in diameter, served as the primary jet until the A Jet's control problems could be solved so that it would operate at a constant pressure throughout a run. The A Jet could be fitted with any of five 12-inch-square or four 27-inch-square nozzles with design speeds between Mach 1.4 and 2.25. Both jets exhausted horizontally toward the south, and models, whether static airplanes or operating ramjets, were mounted on stands immediately outside the nozzle exits. The stands

varied for the different tests, and some included thrust and drag sensors. Ramjet tests also used instruments that measured parameters like temperatures and fuel consumption.[425]

The 125-horsepower air compressor typically needed about 7 hours to pump the air in the spheres, which each measured 28 feet, 10.75 inches in diameter, up to 205 psi. The addition of a second compressor in 1954 cut this time almost in half. A duplex, activated-alumina dryer between the compressors and spheres then dried the air. Its two sides alternated, with one drying air while the other was being reactivated. While air was being stored, the heat exchanger went through its preheat cycle, which took about 4 hours. The heat exchanger consisted of 39,000 ⅛-inch iron pipes 10 feet long that were bundled around an electric heater. Air was circulated around a closed loop through the device until a uniform temperature was achieved in all the pipes. The target temperature, which varied between 280 and 620°F, was calculated to deliver ambient-temperature air after its expansion through each particular nozzle. The electric heater was then turned off for the test run.[426]

With the desired temperature and pressure established, a test began when a technician in the observation house opened the rotovalve, a large, quick-acting valve, to start the air flow. For a ramjet test, the technician remotely opened a valve to admit fuel and sparked an igniter as soon as the ignition speed had been reached, after which the engine would—hopefully—roar to life. Closing the rotovalve and fuel valve stopped the run. The tests were of short duration since the volume of air and heater capacity were limited. Run times, ranging from 8 to 125 seconds, depended on the nozzle size and speed used, but long runs were not necessary to ascertain a ramjet's performance. Much like a rocket, one would reach its steady operating state quickly, and many ramjet problems involved fuel ignition rather than continuous operation. The Preflight Jet was tailor-made to investigate these problems using both small prototypes and full-scale engines.

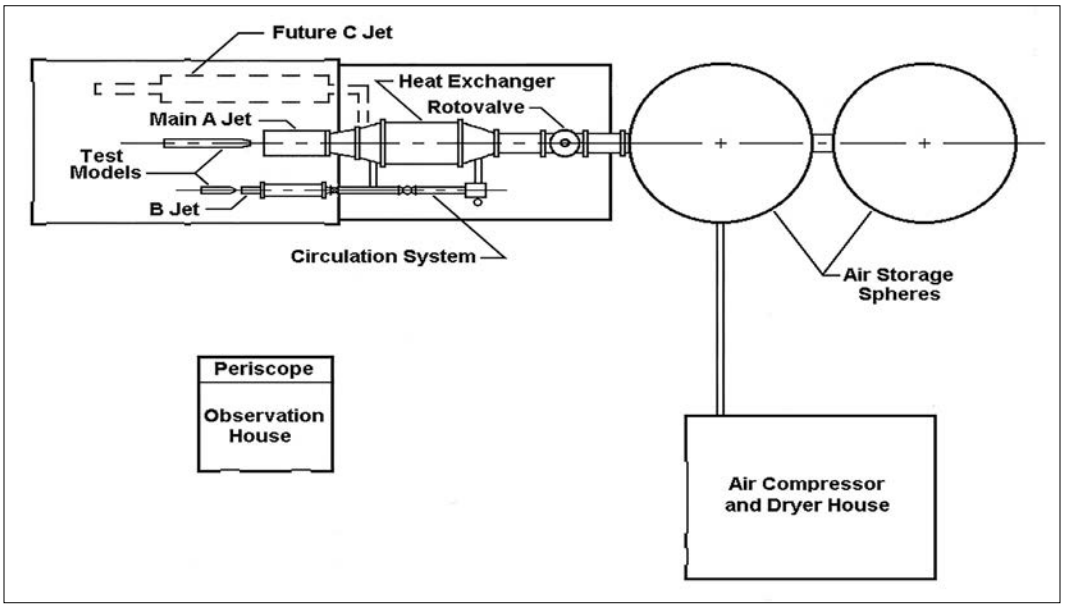
A complex third jet, the High-Altitude Simulator, or C Jet, began operation in 1953, following a three-year design and construction process. It was unlike the A and B jets in that it had an enclosed test section. Some of the compressed air was routed through an ejector to lower the test section pressure to simulate altitudes as high as 80,000 feet. The remaining air flowed through the test section, with a variable portion of it passing around the heat exchanger. Control valves allowed the hot and cold air streams to be mixed to control the air temperature. A unique feature of the C Jet was that the altitude simulator could be rolled out of the way so that an 8-inch jet like the B Jet could use its air supply. Over time, this jet became more useful than the altitude simulator.[427]

In addition to ramjet tests, the Preflight Jet hosted a number of aerodynamic tests at supersonic speeds. Some of the most important concerned stores separation, the way that items like external fuel tanks, bombs, and ejection seats moved when released or ejected from an airplane. It was critical to have designs where this occurred smoothly without the object striking the aircraft after release, and the challenge was especially difficult in supersonic conditions where shock wave interactions frequently caused stores to tumble or otherwise behave in an unsatisfactory manner. These tests utilized a partial

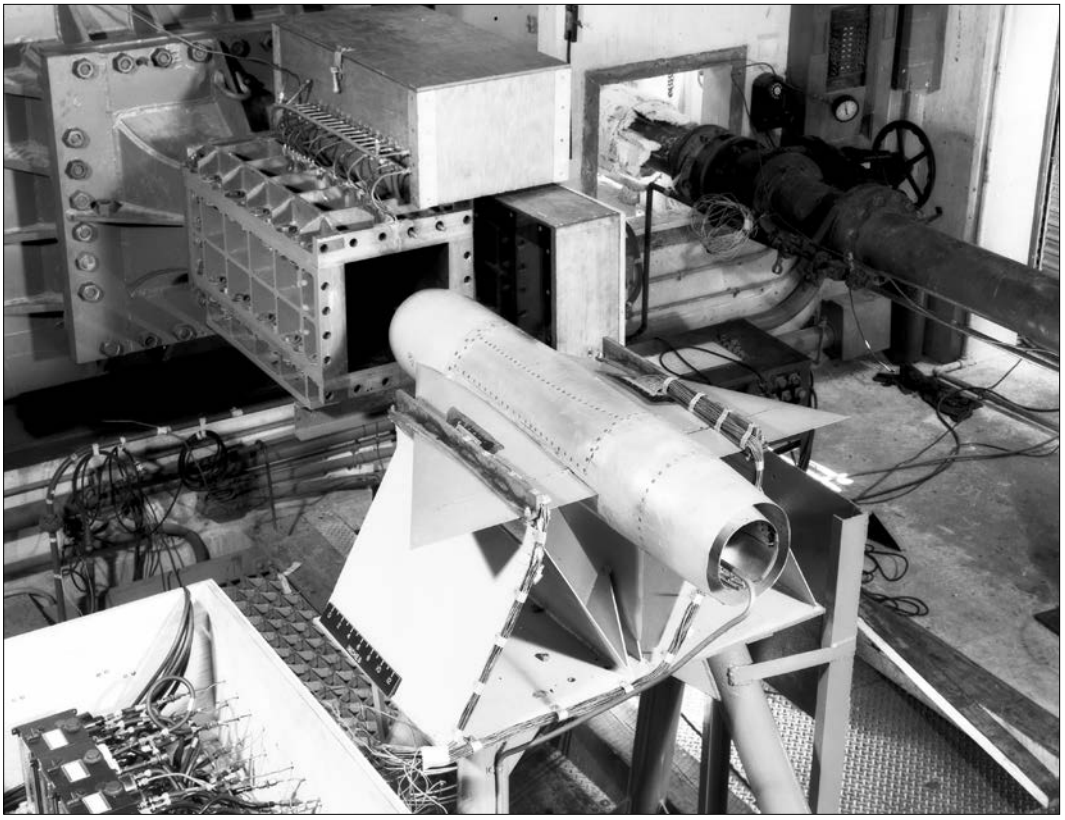
model of an aircraft's fuselage and a dynamically scaled store, and most used the A Jet. Each test was recorded photographically on a single piece of film. The camera's shutter opened for 1/20 second, and a bank of strobe lights flashed at 1/1,000-second intervals, yielding a multi-exposure picture showing the store's track as it left the plane. Between 1953 and 1956, separation tests were run using F-104, F-105, F-106, B-58, and proposed XF-103 models. The facility hosted other aerodynamic tests, including some flutter tests, during the late 1950s.[428]

By 1955, interest in the behavior of materials at high temperatures had grown into a high priority for the NACA, but it had no facilities in which to perform high-temperature testing. Langley engineers began to design some new tunnels for this work, but the first operational facility resulted from a modification to the B Jet at Wallops. The ramjets tested used ethylene (C_2H_4) as fuel, so it was an easy step to install the burner and combustion chamber from a common F23 ramjet ahead of the B Jet's new, 12-inch-diameter nozzle. The result, termed the Ethylene Jet, began service in 1956. Its temperature could be varied from 500 to 4,500°F by adjusting the ethylene fuel flow, and the total pressure continued to be controlled by regulating the air pressure in the heater manifold. With a Mach 2 nozzle, a total pressure of about 12,000 pounds per square foot and a stagnation temperature of about 3,000°F resulted, conditions that simulated Mach 6 flight at 40,000 feet. Test articles were mounted on a hydraulically operated swing arm that rapidly inserted the specimen into the hot jet and extracted it a few seconds later. Under such extreme conditions, most metals failed quickly, often in as little as 2 or 3 seconds. The results of these tests led engineers to redesign components such as rocket fins and to specify more heat-resistant materials.[429]

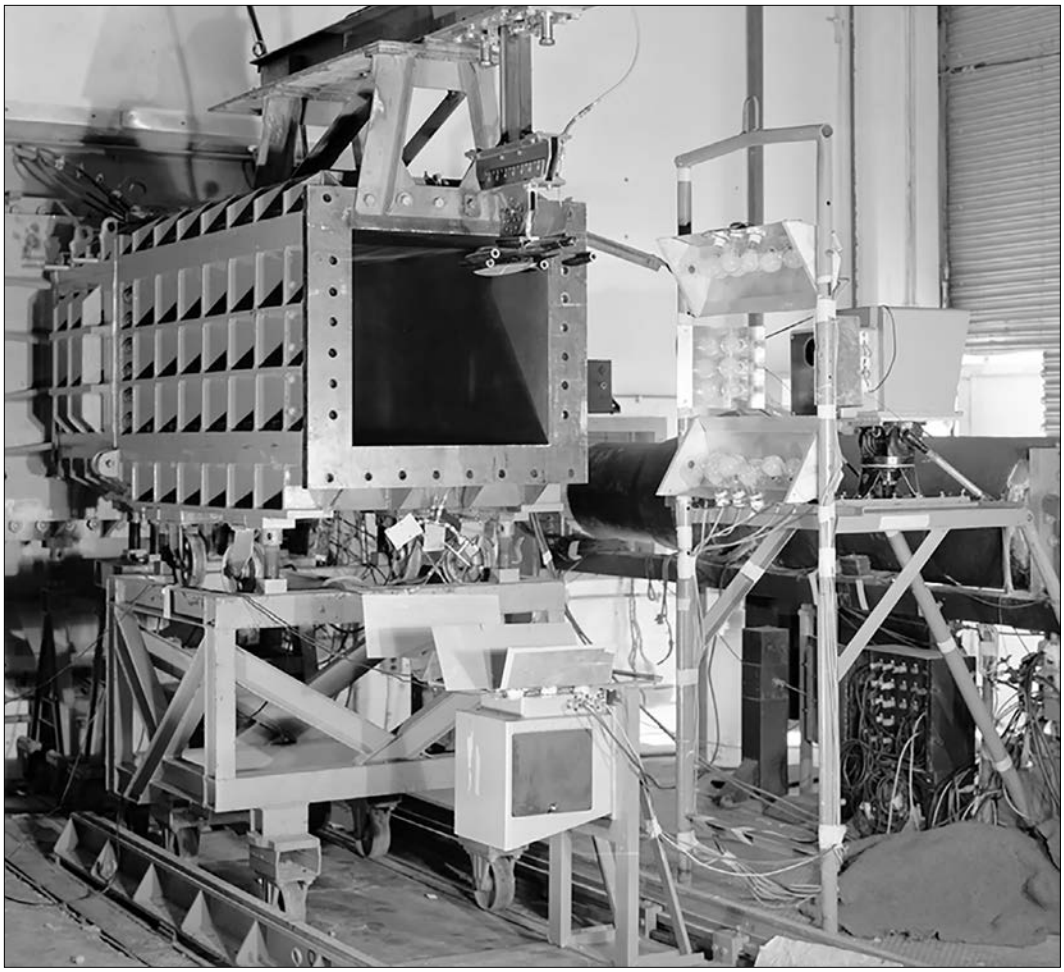
The formation of NASA in 1958 resulted in a reorganization of the former NACA laboratories and stations, as well as a reassessment of all their facilities and activities in light of the new space programs. Wallops Island remained useful as a launch site for small rockets, but NASA administrators foresaw no future for aircraft, engine, or materials research there, especially since newer tunnels at the Langley, Ames, and Lewis centers could handle the needed testing. Thus, the Preflight Jet Facility saw its last test in 1959, and it was decommissioned in October 1960. Over the next few years, usable parts were removed and the remainder gradually dismantled, so virtually nothing remains that is recognizable.[430]



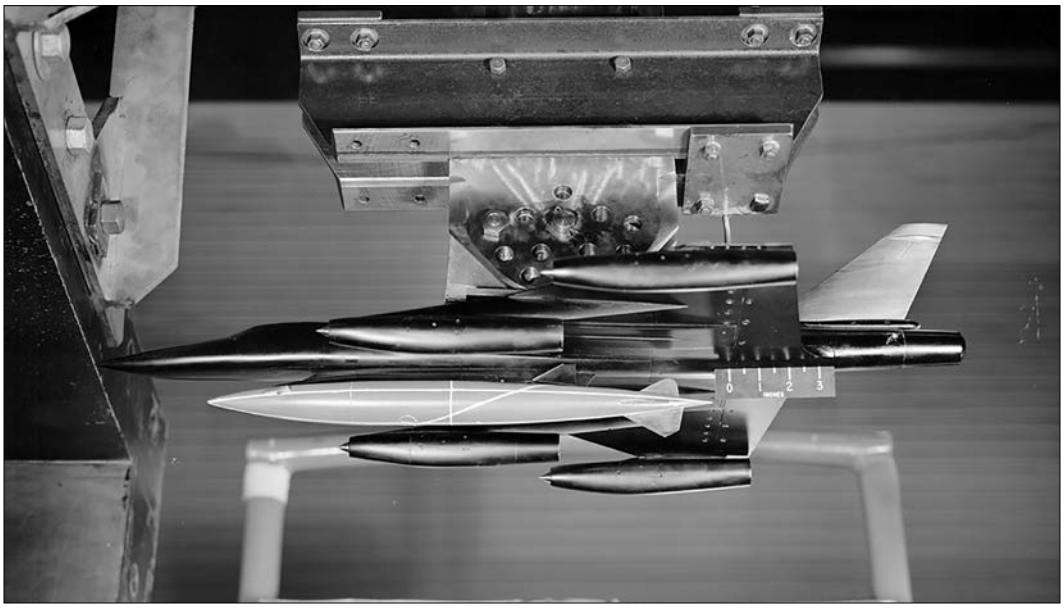
This plan shows the original layout of the Preflight Jet Facility. Compressed air from the spheres passed through the rotovalve, heat exchanger, and one of the jet nozzles to impinge on a model or engine. The High-Altitude C Jet was added in 1953. Not shown is the high-temperature Ethylene Jet that replaced the B Jet in 1956. (Image credit: NASA RP-1028, Fig. 72)



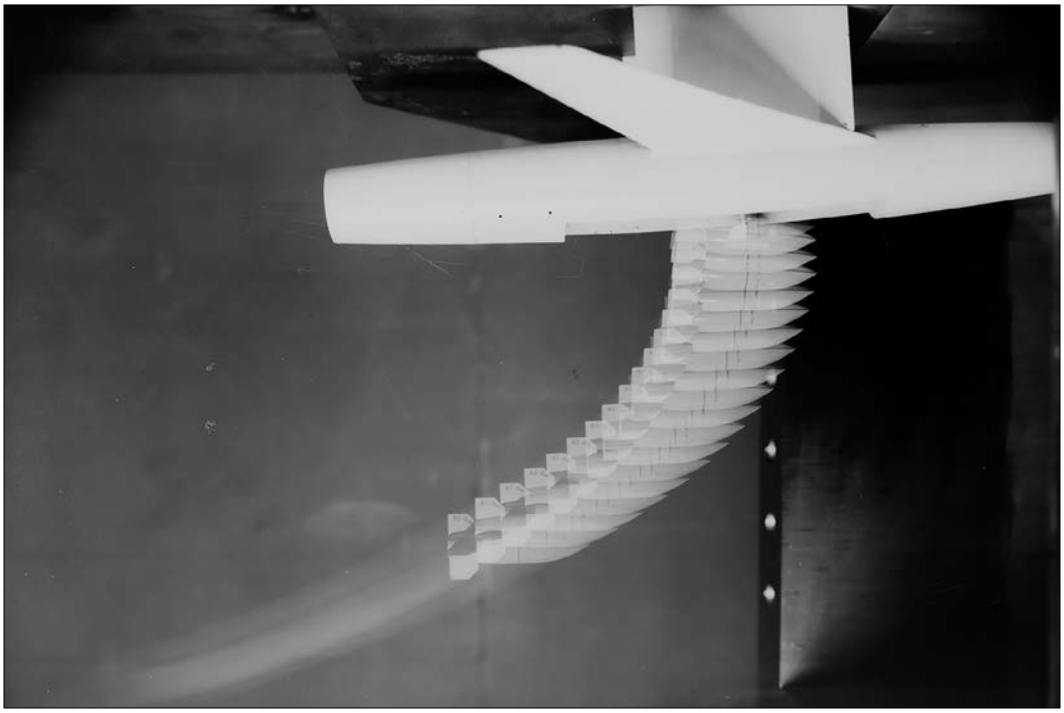
Interior of the Preflight Jet's test house in 1949. The A Jet is in the center, with the B Jet at the right. The high-altitude-simulating C Jet was added out of view to the left. (Photo credit: NASA LRC-1949-B701_P-62807)



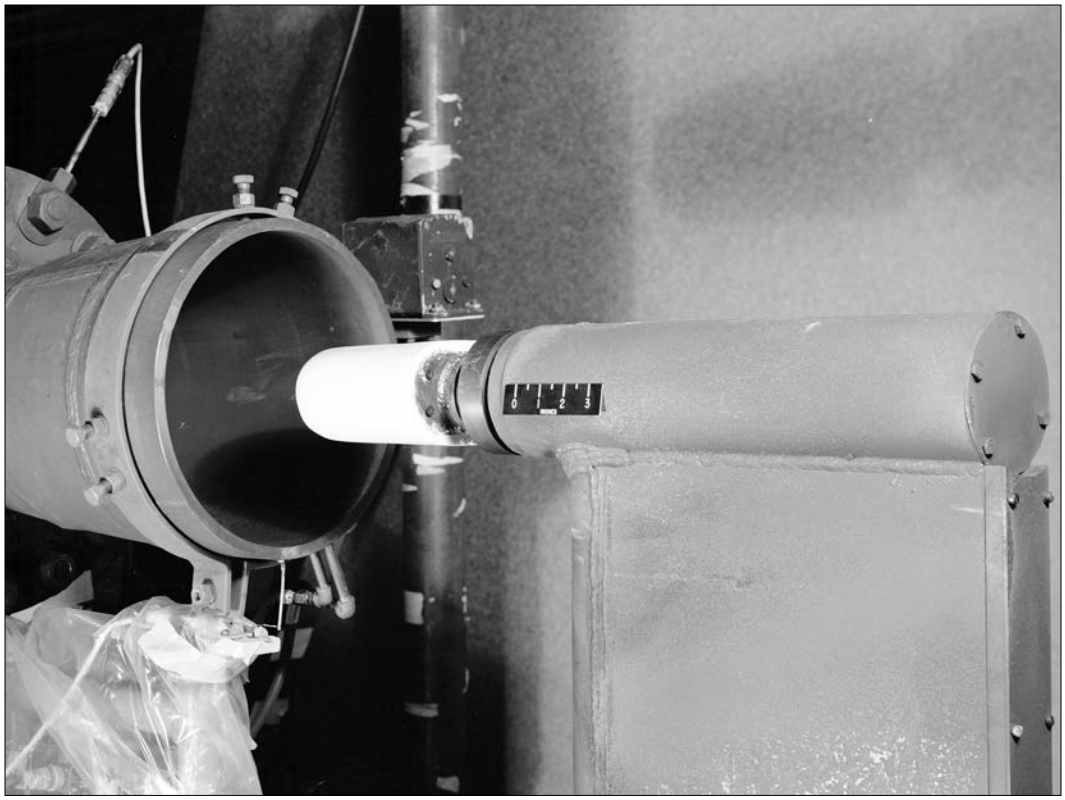
Two views of 1959 testing of a Convair B-58 model two-component fuel pod drops in the facility's A Jet. (Photo credits: NASA LRC-1959-B701_P-02042 and LRC-1959-B701_P-02043)



The facility's doors are rolled up in this 1960 view of a static test of a Scout X transition section. (Photo credit: NASA LRC-1960-B701_P-02923)



This multiple-exposure photograph from 1955 traces the path of a cylindrical bomb with a stabilizing flare after ejection at supersonic speed in the A Jet. The Preflight Jet ran many similar tests. (Photo credit: NASA LRC-1955-B701_P-91299)



Testing of ablation models in the Pre Flight's B Jet in 1959. (Photo credit: NASA LRC-1959-B701_P-02876)

ENDNOTES

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3 Speech of Rear Adm. D. W. Taylor, USN, Langley Field, 11 June 1920, copy in Milton Ames Collection.

4 For a history of the Wallops Flight Facility, see Harold D. Wallace, Jr., *Wallops Station and the Creation of an American Space Program* (Washington, DC: NASA SP-4311, 1997).

5 Descriptive data were gleaned from F. H. Norton, "National Advisory Committee's 5-Ft. Wind Tunnel," *Journal of the Society of Automotive Engineers* (May 1921): 1–7.

6 Donald D. Baals and William R. Corliss, *Wind Tunnels of NASA* (Washington, DC: NASA, 1981), pp. 14–15.

7 J. Lawrence Lee, "Into the Wind: A History of the American Wind Tunnel, 1896–1941" (Ph.D. diss., Auburn Univ., 2001), pp. 56–60.

8 William F. Durand, "The Aerodynamic Laboratory at Leland Stanford Junior University and the Equipment Installed with Special Reference to Tests on Air Propellers," *Technical Report 14* (Washington, DC: NACA, 1917).

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11 Max M. Munk, "Preliminary Wing Model Tests in the Variable Density Wind Tunnel of the National Advisory Committee for Aeronautics," *Technical Report 217* (Washington, DC: NACA, 1925). Also Max M. Munk, "Model Tests with a Systematic Series of 27 Wing Sections at Full Reynolds Number," *Technical Report 221* (Washington, DC: NACA, 1925).

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15 Wladimir Margoulis, "A New Method of Testing Models in Wind Tunnels," *Technical Note 52* (Washington, DC: NACA, 1921).

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17 James R. Hansen, *Engineer in Charge: A History of the Langley Aeronautical Laboratory, 1917-1958* (Washington, DC: NASA, 1987), p. 100. Also Eastman N. Jacobs and Ira H. Abbott, "The N.A.C.A. Variable-Density Wind Tunnel," *Technical Report 416* (Washington, DC: NACA, 1932), pp. 305–307.

18 See the Langley 11-Inch High-Speed Tunnel and 24-Inch High-Speed Tunnel sections for further details.

19 Description and performance data are from Fred E. Weick and Donald H. Wood, "The Twenty-Foot Propeller Research Tunnel of the National Advisory Committee for Aeronautics," *Technical Report 300* (Washington, DC: NACA, 1928).

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21 Weick and Wood, *Technical Report 300*, p. 434.

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23 Ibid., pp. 437.

24 For a detailed discussion of the cowling program, see chapter 5 of Hansen, *Engineer in Charge*, pp. 123–139.

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29 A typical report of these airfoil tests is John Stack and W. F. Lindsey, "Tests of N-85, N-86, and N-87 Airfoil Sections in the 11-Inch High Speed Wind Tunnel," *Technical Note 665* (Washington, DC: NACA, 1933).

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37 Description and performance data are from Smith J. DeFrance, "The NACA Full-Scale Wind Tunnel," *Technical Report 459* (Washington, DC: NACA, 1933).

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41 Ibid., pp. 296–297.

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51 See the Langley 6- by 19-Inch Transonic Tunnel section.

52 Descriptive and performance data were compiled from several sources, including C. H. Zimmerman, "Preliminary Tests in the N.A.C.A. Free-Spinning Wind Tunnel," *Technical Report 557* (Washington, DC: NACA, 1936); Hansen, *Engineer in Charge*, p. 453; Alexander Klemin, "Langley Field Engineering Conference," *Aero Digest* 26, no. 6 (June 1935): 20; NASA photographs EL-2001-00111, EL-2001-00112, and EL-2001-00113; and author's conversations with Langley employees Joseph R. Chambers (retired) and Earl Harris, 8 Sept. 2008.

53 Zimmerman, *Technical Report 557*. Also Hansen, p. 453. The 150-horsepower figure is contradicted in a 1942 memorandum noting the performance of Langley's 15-Foot and 20-Foot spin tunnels, where a value of 338 horsepower (short-time rating; about 325 horsepower continuously) is given. Both sources, however, cite the same maximum speed: 60 feet per second (40 miles per hour). See Memorandum, Oscar Seidman to Chief Aerodynamics Division, re: Spin tunnels at LMAL, 28 Feb. 1942, Record Group 255, A206-1, Box 430, National Archives and Records Administration, Philadelphia, PA.

54 See the Langley 5-Foot Vertical Wind Tunnel section for details.

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56 Ibid., pp. 3–4.

57 Ibid., p. 2.

58 Ibid., pp. 2–3.

59 Klemin, *Aero Digest*, p. 20.

60 Zimmerman, *Technical Report 557*, p. 3.

61 Memorandum, Oscar Seidman to Chief Aerodynamics Division, re. Spin tunnels at LMAL, 28 Feb. 1942. Also Baals and Corliss, *Wind Tunnels of NASA*, pp. 42–43. See also Mary Gainer, "NASA Langley Research Center Historic Sites and Buildings," *http://crgis.ndc.nasa.gov/historic/Free_Spinning_Tunnel*.

62 Description and performance data are from Robert C. Stewart, *NASA Langley Research Center, 8-Foot High-Speed Wind Tunnel*, HAER No. VA-118-B (Washington, DC: Historic American Engineering Record, 1995), pp. 6–9. Also James R. Hansen, *Engineer in Charge: A History of the Langley Aeronautical Laboratory, 1917–1958* (Washington, DC: NASA, 1987), p. 454.

63 Inspection by Caroline A. Diehl, Sr. Environmental Protection Specialist, Science Applications International Corporation (SAIC), and author, 10 Sept. 2008.

64 Baals and Corliss, *Wind Tunnels of NASA*, pp. 24–27.

65 Ibid., pp. 27–28.

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75 Joseph A. Shortal and Clayton J. Osterhout, "Preliminary Stability and Control Tests in the NACA Free-Flight Wind Tunnel and Correlation with Full-Scale Flight Tests," *Technical Note 810* (Washington, DC: NACA, 1941), pp. 2–3.

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81 Shortal and Osterhout, *Technical Note 810*, p. 3.

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83 Jacobs and Rowland, "12-Foot Low-Speed Tunnel," p. 2.

84 Unlike most Langley wind tunnels, the NACA did not publish a technical note or report describing the 19-Foot PT, nor were its characteristics fully described in other research publications. Thus, these descriptive and performance data were collectively gleaned from several unnumbered drawings, photographs, and property records, as well as Baals and Corliss, *Wind Tunnels of NASA*, pp. 28–29; and Hansen, *Engineer in Charge*, pp. 459–462.

85 During the 1930s, reports from John Jay Ide's office in Paris began to describe new German and Italian facilities seemingly geared for high-speed research. A 1936 visit by George Lewis confirmed Ide's analysis, especially concerning the five new facilities with large staffs in Nazi Germany. See Hansen, *Engineer in Charge*, p. 188.

86 The concept, never put into service, was for the huge bomber to convey the fighters to the target area, where they could start their jet engines, disconnect, and protect the bomber. Reconnection for the trip home was a problem never solved, and the tests showed that low-speed flutter was possible, especially during roll maneuvers.

87 Reports describing these tests include Robert R. Graham and C. Dixon Ashworth, "Tests in the 19-Foot Pressure Tunnel of a $^1/_{2.75}$–Scale Model of the F4U-1 Airplane with Several Balanced Elevators, Full-Span Flaps, and Droppable Gas Tank," NACA *Advance Confidential Report L-440* (Washington, DC: NACA, 1942); S. R. Alexander and James C. Sivells, "Tests of a $^1/_{14}$–Scale Powered Model of the XB-36 Airplane in the Langley 19-Foot Pressure Tunnel: I–Stalling Characteristics and Aileron Effectiveness of Several Wing and Flap Arrangements," NACA *Memorandum Report L5B23* (Washington, DC: NACA, 1945); Gerald G. Kayten and William Koven, "Comparison of Wind-Tunnel and Flight Measurements of Stability and Control Characteristics of a Douglas A-26 Airplane," *Technical Report 816* (Washington, DC: NACA, 1945); and Robert H. Neely, "Flutter Tests of a $^1/_{25}$–Scale Model of the B-36J/RF-84F Tip-Coupled Airplane Configuration in the Langley 19-Foot Pressure Tunnel," NACA *Research Memorandum SL56A25b* (Washington, DC: NACA, 1956).

88 For an outline of aeroelasticity research, see Rodney H. Ricketts, "Experimental Aeroelasticity History, Status and Future in Brief," NASA *Technical Memorandum 102651* (Washington, DC: NASA, 1990).

89 Descriptive and performance data were compiled from "Langley Research Center Facilities," *Technical Memorandum 109685* (Washington, DC: NASA, 1993), pages not numbered; William T. Schaefer, Jr., "Characteristics of Major Active Wind Tunnels at the Langley Research Center," *Technical Memorandum X-1130* (Washington, DC: NASA, 1965), p. 41; and "Wind Tunnels at NASA Langley Research Center," *FS-2001-04-64-LaRC* (Washington, DC: NASA, 2000), p. 3.

90 Ralph W. Stone, Jr., Sanger M. Burk, Jr., and William Bihrle, Jr., "The Aerodynamic Forces and Moments on a $^1/_{10}$–Scale Model of a Fighter Airplane in Spinning Attitudes as Measured on a Rotary Balance in the Langley 20-Foot Free-Spinning Tunnel," *Technical Note 2181* (Washington, DC: NACA, 1950), pp. 5–6.

91 "20-Foot Vertical Spin Tunnel, Langley Research Center" (Hampton, VA: LaRC, n.d.), p. 3.

92 William Bihrle, Jr., Randy S. Hultberg, and William Mulcay, "Rotary Balance Data for a Typical Single-Engine Low-Wing General Aviation Design for an Angle-of-Attack Range of 30° to 90°," *Contractor Report 2972* (Washington, DC: NASA, 1978), pp. 4–5. Also author's conversation with NASA Langley employees Earl Harris and Lee Pollard, 8 Sept. 2008.

93 Hansen, *Engineer in Charge*, p. 462. For a description and brief history of the Wright Field Vertical Wind Tunnel, see *Wright-Patterson Air Force Base, Area B, Building 27, Vertical Wind Tunnel*, HAER No. OH-79-A (Washington: Historic American Engineering Record, 1993), pp. 2–5.

94 While Langley's Propeller Research Tunnel and Full Scale Tunnel used their outer walls as both tunnel walls and building structure, the NACA's first truly outside tunnel was the 8-Foot High-Speed Tunnel, constructed of reinforced concrete and opened in 1936.

95 Previous wind tunnels fabricated by Pittsburgh–Des Moines Steel were the Wright Brothers Memorial Wind Tunnel at MIT (1938) and the 19-Foot Pressure Tunnel at NACA Langley (1939).

96 For dimensional and performance data, see Building Data/Ledger Sheets, pages 84–86, of Real Property Files, maintained at NASA Langley Research Center Building 1238. For other design and operation details, see Albert E. von Doenhoff and Frank T. Abbott, Jr., "The Langley Two-Dimensional Low-Turbulence Pressure Tunnel," NACA *Technical Note 1283* (Washington, DC: NACA, 1947), pp. 11–15.

97 Building Data/Ledger Sheets, p. 85.

98 Ibid., p. 85.

99 "Research and Test Facilities: Langley Research Center," *Technical Memorandum 109685* (Washington, DC: NASA, 1 Jan. 1993), pages not numbered. Also caption for NASA image EL-1996-00040, "Low-Turbulence Pressure Tunnel Research Complex Aerial," 19 Mar. 1993.

100 "Aeronautical Facilities Catalog: Volume 1, Wind Tunnels," *Research Publication 1132* (Washington, DC: NASA, 1985), p. 122.

101 Felicien F. Fullmer, Jr., "Tests of a $^{1}/_{40}$–Scale Wing-Hull Model and a $^{1}/_{10}$–Scale Float-Strut Model of the Hughes-Kaiser Cargo Airplane in the Two-Dimensional Low-Turbulence Pressure Tunnel," NACA *Wartime Report L-633* (Washington, DC: NACA, 1943).

102 *Research Publication 1132*, p. 122.

103 The NACA did not publish a descriptive paper for the original tunnel, so most dimensional data were measured from available drawings and must be considered approximate. Most Transonic Tunnel performance figures are from Francis J. Capone, Linda S. Bangert, Scott C. Asbury, Charles T. L. Mills, and Ann Bare, "The NASA Langley 16-Foot Transonic Tunnel," *Technical Paper 3521* (Washington, DC: NASA, 1995).

104 Capone, Bangert, Asbury, Mills, and Bare, "The NASA Langley 16-Foot Transonic Tunnel," pp. 3–6.

105 Ibid., pp. 5–6.

106 Ibid., p. 7.

107 The earliest use of the term "design revolution" to describe the extensive changes in airplane design and construction during the late 1920s and 1930s appears to be by Laurence K. Loftin, Jr., an NACA/NASA researcher and manager, who used it as the title for chapter 4 of his book, *Quest for Performance: The Evolution of Modern Aircraft* (Washington, DC: NASA, 1987).

108 Hansen, *Engineer in Charge*, pp. 192–194. Also Elizabeth A. Muenger, *Searching the Horizon: A History of Ames Research Center*, 1940–1976 (Washington, DC: NASA, 1981), p. 3.

109 Baals and Corliss, *Wind Tunnels of NASA*, pp. 33, 36. Also Hansen, *Engineer in Charge*, p. 464.

110 Baals and Corliss, *Wind Tunnels of NASA*, p. 37.

111 Ibid., p. 37. Also Albert J. Evans and George Liner, "A Wind-Tunnel Investigation of the Aerodynamic Characteristics of a Full-Scale Supersonic-Type Three-Blade Propeller at Mach Numbers to 0.96," *Research Memorandum L53F01* (Washington, DC: NACA, 1953).

112 The descriptive data for facilities shown here are from H. J. E. Reid to [Ralph E.] Ulmer, re: List of supersonic facilities, 27 Oct. 1947, National Archives and Records Administration, Mid-Atlantic Region Facility, Philadelphia, PA, Record Group 255, Box 422.

113 John V. Becker, *The High-Speed Frontier: Case Histories of Four NACA Programs, 1920–1950* (Washington, DC: NASA, 1980), pp. 100–102.

114 Hansen, *Engineer in Charge*, pp. 464–466. Also Capone, Bangert, Asbury, Mills, and Bare, "The NASA Langley 16-Foot Transonic Tunnel," pp. 1, 4–5, 19–22.

115 Capone, Bangert, Asbury, Mills, and Bare, "The NASA Langley 16-Foot Transonic Tunnel," pp. 7–8.

116 Ibid., p. 2.

117 Ibid., pp. 10–11.

118 Typical reports of test programs include D. E. Reubush and J. R. Carlson, "Effects of Installation of F101 DFE Exhaust Nozzles on the Afterbody-Nozzle Characteristics of the F-14 Airplane," *Technical Memorandum 83250* (Washington, DC: NASA, 1982); and Francis J. Capone, Mary L. Mason, and George T. Carson, Jr., "Aeropropulsive Characteristics of Canted Twin Pitch-Vectoring Nozzles at Mach 0.20 to 1.20," *Technical Paper 3060* (Washington, DC: NASA, 1991).

119 Bill Uher, "NASA's 16-Foot Transonic Tunnel Leaves Powerful Legacy" (Washington, DC: NASA, 24 Sept. 2004), pp. 1–2, *http://www.nasa.gov/vision/earth/improvingflight/ 16ft.html.*

120 The NACA did not publish a descriptive paper for this tunnel, so most dimensional data were measured from available drawings and must be considered approximate. For performance data, see Hansen, *Engineer in Charge*, p. 466. Also "Stability Wind Tunnel Description," Virginia Tech Department of Aerospace and Ocean Engineering, 18 Sept. 2008, *http://www.aoe.vt.edu/research/facilities/stab/tunnel_descrip.php.*

121 Baals and Corliss, *Wind Tunnels of NASA*, pp. 43–44.

122 No record of the names of the Stability Tunnel's designers has been located; however, two of the more prolific authors/coauthors of technical reports based on work done in it were Lewis R. Fisher and John D. Bird. This is no guarantee that either participated in the tunnel's design and construction, but it was common at Langley for tunnel design engineers to also have been leaders of the early research work performed in facilities they designed.

123 This balance is not described in any NACA technical paper, but the mechanical scales and electrical components can be discerned in NACA photo L-32201.

124 John D. Bird, Byron M. Jaquet, and John W. Cowan, "Effect of Fuselage and Tail Surfaces on Low-Speed Yawing Characteristics of a Swept-Wing Model as Determined in Curved-Flow Test Section of Langley Stability Tunnel," *Technical Note 2483* (Washington, DC: NACA, 1951), p. 2. Note that this publication supersedes identically titled, but classified, *Research Memorandum L8G13*, dated 1948, closer to the time the work was done.

125 Ibid., pp. 4–5.

126 Typical of these reports were Jack D. Brewer and Lewis R. Fisher, "Effect of Taper Ratio on the Low-Speed Rolling Stability Derivatives of Swept and Unswept Wings of Aspect Ratio 2.61," *Research Memorandum L8H18* (Washington, DC: NACA, 1948), pp. 7–8; Alex Goodman and Lewis R. Fisher, "Investigation at Low Speeds of the Effect of Aspect Ratio and Sweep on Rolling Stability Derivatives of Untapered Wings," *Technical Note 1835* (Washington, DC: NACA, 1949), p. 11; and Lewis R. Fisher, "Some Effects of Aspect Ratio and Tail Length on the Contribution of a Vertical Tail to Unsteady Lateral Damping and Directional Stability of a Model Oscillating Continuously in Yaw," *Technical Note 3121* (Washington, DC: NACA, 1953), p. 17.

127 "Stability Wind Tunnel," Virginia Tech Department of Aerospace and Ocean Engineering, 7 Aug. 2008, *http://www.aoe.vt.edu/research/facilities/stab/*.

128 Hansen, *Engineer in Charge*, p. 467.

129 Material describing the 9-Inch SWT is unusually rare and lacking in detail. As with most other facilities built during World War II, the NACA did not publish a paper detailing its features and capabilities, and technical reports of test programs through the late 1950s each included only a brief, general paragraph that was almost identical. Thus, the descriptive material was compiled from brief specifications in Hansen, *Engineer in Charge*, p. 467; Alex Roland, *Model Research: The National Advisory Committee for Aeronautics, 1915–1958*, vol. 2 (Washington, DC: NASA, 1985), p. 521; and James J. Gallagher and James N. Mueller, "An Investigation of the Maximum Lift of Wings at Supersonic Speeds," *Technical Report 1227* (Washington, DC: NACA, 1955), p. 3. Additional information was gleaned from the NACA photographs and the author's inspection of the tunnel as it currently exists at Blacksburg, Virginia.

130 "U. S. and Foreign Wind Tunnels in Operation, under Construction, or Authorized," *AR 26/11.5* (Washington, DC: Research and Development Board, Committee on Aeronautics, 1948), quoted in Roland, *Model Research*, p. 521.

131 "Supersonic Wind Tunnel," Dept. of Aerospace and Ocean Engineering, Virginia Polytechnic Institute and State University, 23 Jan. 2006, pp. 1–2, *http://www.aoe.vt.edu/research/facilities/superso.php*. Also Professors Joseph Schetz and William Devenport, conversations with author, 27 Mar. 2009.

132 Hansen, *Engineer in Charge*, p. 36. Also John D. Anderson, Jr., *The Airplane: A History of Its Technology* (Reston, VA: The American Institute of Aeronautics and Astronautics [AIAA], 2002), pp. 307–308.

133 Hansen, *Engineer in Charge*, p. 250.

134 Roland, *Model Research*, p. 521. Also Robert W. Rainey, "Langley 9-Inch Supersonic Tunnel Tests of Several Modifications of a Supersonic Missile Having Tandem Cruciform Lifting Surfaces," *Research Memorandum L50I29a* (Washington, DC: NACA, 1951), pp. 1, 3.

135 Hansen, *Engineer in Charge*, pp. 250, 467.

136 Typical reports for this period include D. Adamson and William B. Boatright, "Investigation of Downwash, Sidewash, and Mach Number Distribution Behind a Rectangular Wing at a Mach Number of 2.41," *Research Memorandum L50G12*, 1950; Carl E. Grigsby, "Tests at Mach Number 1.62 of a Series of Missile Configurations Having Tandem Cruciform Lifting Surfaces," *Research Memorandum L51J15*, 1952; and August F. Bromm, Jr., "Investigation of Lift, Drag, and Pitching Moment of a 60° Delta-Wing-Body Combination (AGARD Calibration Model B) in the Langley 9-Inch Supersonic Tunnel," *Technical Note 3300*, 1954; all Washington, DC: NACA.

137 "Supersonic Wind Tunnel," pp. 1–2. Also Schetz and Devenport, conversations with author, 27 March 2009.

138 The NACA did not publish a descriptive paper for the original tunnel, so most dimensional data were measured from available drawings and must be considered approximate. For performance data, see William T. Schaefer, Jr., "Characteristics of Major Active Wind Tunnels at the Langley Research Center," *Technical Memorandum X-1130* (Washington, DC: NASA, July 1965), p. 57; and Hansen, *Engineer in Charge*, p. 467. These data are supported by a table attached to H. J. E. Reid to NACA Headquarters, re: Proposed specifications for eight research facilities of the Langley Laboratory, 24 Jan. 1956, National Archives and Records Administration, Mid-Atlantic Region Facility, Philadelphia, PA, Record Group 255, Box 429.

139 Thomas A. Harris, "Documentation of the 300-Mile per Hour 7- by 10-Foot Wind Tunnel," (Hampton, VA: LaRC, March 1972), p. 3. Also Hansen, *Engineer in Charge*, p. 192.

140 Ibid., pp. 5, 10–11, figure 17. Also Hansen, *Engineer in Charge*, p. 467.

141 Harris, "Documentation," pp. 1–2.

142 Hansen, *Engineer in Charge*, pp. 192–193. Also Harris, "Documentation," pp. 2–3.

143 Typical of the numerous technical reports that published the results of such tests is Leslie E. Schneiter and James M. Watson, "Low-Speed Wind-Tunnel Investigation of Various Plain-Spoiler Configurations for Lateral Control on a 42° Sweptback Wing," *Technical Note 1646* (Washington, DC: NACA, 1948). The title is indicative of how closely focused many of these test programs were. For a brief background on swept wings, see George W. Gray, *Frontiers of Flight: The Story of NACA Research* (New York: Alfred A. Knopf, 1948), pp. 341–344.

144 Harris, "Documentation," p. 5.

145 Ibid., p. 5. Also *Characteristics of Nine Research Wind Tunnels of the Langley Aeronautical Laboratory* (Washington, DC: NACA, 1957), p. 70.

146 The NACA did not publish a descriptive paper for the original tunnel, so most dimensional data were measured from available drawings and must be considered approximate. For performance data, see William T. Schaefer, Jr., "Characteristics of Major Active Wind Tunnels at the Langley Research Center," *Technical Memorandum X-1130* (Washington, DC: NASA, July 1965), p. 38; and Hansen, *Engineer in Charge*, pp. 469–470. These data are supported by a table attached to H. J. E. Reid to NACA Headquarters, re: Proposed specifications for eight research facilities of the Langley Laboratory, 24 Jan. 1956, National Archives and Records Administration, Mid-Atlantic Region Facility, Philadelphia, PA, Record Group 255, Box 429.

147 Thomas A. Harris, "Documentation of the 300-Mile per Hour 7- by 10-Foot Wind Tunnel" (Hampton, VA: LaRC, March 1972), pp. 1–2.

148 Hansen, *Engineer in Charge*, pp. 192–193. Also Harris, "Documentation," pp. 2–3.

149 One such early report is Leslie E. Schneiter and John R. Hagerman, "Wind-Tunnel Investigation at High Subsonic Speeds of the Lateral-Control Characteristics of an Aileron and a Stepped Spoiler on a Wing with Leading Edge Swept Back 51.3°," *Research Memorandum L9D06* (Washington, DC: NACA, 1951). For a brief background on swept wings, see Gray, *Frontiers of Flight*, pp. 341–344.

150 Harris, "Documentation," p. 5. Also William D. Morrison, Jr., and Paul G. Fournier, "Effects of Spanwise Thickness Variation on the Aerodynamic Characteristics of 35° and 45° Sweptback Wings of Aspect Ratio 6: Transonic Bump Method," *L51D19* (Washington, DC: NACA, 1951), pp. 4–6, 19.

151 Schaefer, *Technical Memorandum X-1130*, p. 38.

152 A small sample of these publications include Leslie E. Schneiter and Howard L. Ziff, "Preliminary investigation of Spoiler Lateral Control on a 42° Sweptback Wing at Transonic Speeds," *Research Memorandum L7F19* (Washington, DC: NACA, 1947); Kenneth P. Spreeman and William J. Alford, Jr., "Investigation of the Effects of Twist and Camber on the Aerodynamic Characteristics of a 50° 38' Sweptback Wing of Aspect Ratio 2.98: Transonic Bump Method," *L51C16*, (Washington, DC: NACA, 1951); and Edward C. Polhamus, "Summary of Results Obtained by Transonic-Bump Method on Effects of Plan Form and Thickness on Lift and Drag Characteristics of Wings at Transonic Speeds," *Technical Note 3469* (Washington, DC: NACA, 1955).

153 William J. Alford, Jr. and Robert T. Taylor, "Aerodynamic Characteristics of the X-15/B-52 Combination," *National Technical Reports Server Accession No. 93R21676* (Washington, DC: NACA, 1958). Also Delma C. Freeman, Jr., and Richard P. Boyden, "Dynamic Stability Characteristics of the Combination Space Shuttle Orbiter and Ferry Vehicle," *Technical Memorandum X-3497.*

154 Richard W. Faison, "Analysis of 7- × 10-Foot High Speed Wind Tunnel Shaft Loads in Support of Fan Blade Failure Investigation," *Technical Memorandum 100504* (Washington, DC: NASA, 1987).

155 Robert M. Hall, Gary E. Erikson, Charles H. Fox, Daniel W. Banks, and David E. Fisher, "Evaluation of Gritting Strategies for High Angle of Attack Using Wind Tunnel and Flight Test Data for the F/A-18," *Technical Paper 1998-207670* (Washington, DC: NASA, 1998).

156 Photographs showing dark models imply that light-colored background panels may have been used as well; however, one testing technique used in an earlier apparatus involved placing small lights on the model, and dark models were used with dark backgrounds to improve photographic capture of light traces. Unfortunately, the technical reports of tests in the later facility fail to elaborate on this aspect of the testing technique.

157 Philip Donely, "Summary of Information Relating to Gust Loads on Airplanes," *Technical Report 997* (Washington, DC: NACA, 1949), p. 18.

158 J. C. Hunsaker, "Report on Behavior of Aeroplanes in Gusts: Part I—Experimental Analysis of Inherent Longitudinal Stability for a Typical Biplane," *Report No. 1* (Springfield, VA: United States Department of Commerce, 1915). E. B. Wilson authored "Part II—Theory of an Aeroplane Encountering Gusts." This two-part report was also cataloged as *Technical Report 1* by the NACA.

159 Philip Donely, "An Experimental Investigation of the Normal Acceleration of an Airplane Model in a Gust," *Technical Note 706* (Washington: NACA, 1939), p. 4.

160 Ibid., pp. 5–6.

161 Typical reports of these tests are Philip Donely and C. C. Shufflebarger, "Tests in the Gust Tunnel of a Model of the XBM-1 Airplane," *Technical Note 731* (Washington, DC: NACA, 1939); Philip Donely, Harold B. Pierce, and Philip W. Pepoon, "Measurements and Analysis of the Motion of a Canard Airplane Model in Gusts," *Technical Note 758* (Washington, DC: NACA, 1940); C. C. Shufflebarger, "Tests of a Gust-Alleviating Wing in the Gust Tunnel," *Technical Note 802* (Washington, DC: NACA, 1941); and Thomas D. Reisert, "Tests of a 1/17-Scale Model of the XBDR-1 Airplane in the NACA Gust Tunnel," *Wartime Report L-539* (Washington, DC: NACA, 1944). Also Gray, *Frontiers of Flight*, pp. 172–174.

162 Donely, *Technical Report 997*, pp. 19, 45. Also Hansen, *Engineer in Charge*, p. 468.

163 Typical reports investigating the theoretical and empirical aspects of a gust issue are Robert T. Jones, "Correction of the Lifting-Line Theory for the Effect of Chord," *Technical Note 817* (Washington, DC: NACA, 1941); and Harold B. Pierce and Mitchell Trauring, "Gust-Tunnel Tests to Determine Influence of Airfoil Section Characteristics on Gust-Load Factors," *Technical Note 1632* (Washington, DC: NACA, 1948). Both reports explore the effects of airfoil shape on gust performance.

164 Hansen, *Engineer in Charge*, p. 468.

165 No complete description of this tunnel is known to exist. Descriptive data have been compiled from Hansen, *Engineer in Charge*, 1987), p. 469; Alex Roland, *Model Research: The National Advisory Committee for Aeronautics, 1915–1958*, Vol. 2 (Washington, DC: NASA, July 1985), p. 521; and Harry L. Runyan and John Sewall, "Experimental Investigation of the Effects of Concentrated Weights on Flutter Characteristics of a Straight Cantilever Wing," *Technical Note 1594* (Washington, DC: NACA, 1948), p. 3.

166 I. E. Garrick, "Some High-Speed Flutter Studies," *Aeronautical Problems of Transonic Airplane Design* (Moffett Field, CA: NACA Ames Aeronautical Laboratory, 1947), p. 82.

167 Early references include Runyan and Sewall, *Technical Note 1594*, p. 3. Later references include Hansen, *Engineer in Charge*, p. 469; and Roland, *Model Research*, p. 521.

168 For a more detailed history and explanation of aeroelasticity and flutter, see I. E. Garrick and Wilmer H. Reed III, "Historical Development of Aircraft Flutter," *Journal of Aircraft* (Nov. 1981): 897–912. Also Hubert I. Flomenhoft, *The Revolution in Structural Dynamics* (Palm Beach Gardens, FL: Dynaflo Press, 1997). For an engineering treatise, see Raymond L. Bisplinghoff and Holt Ashley, *Principles of Aeroelasticity* (Hoboken, NJ: John Wiley and Sons, 1962).

169 I. E. Garrick, "Some High-Speed Flutter Studies," p. 79.

170 Runyan and Sewall, *Technical Note 1594*, p. 3. Also George E. Castile and Robert W. Herr, "Some Effects of Density and Mach Number on the Flutter Speed of Two Uniform Wings," *Technical Note 1989* (Washington, DC: NACA, 1949), p. 3.

171 Runyan and Sewall, *Technical Note 1594*, pp. 3–5.

172 Typical test reports of the period include Robert W. Herr, "Preliminary Experimental Investigation of Flutter Characteristics of M and W Wings," *Research Memorandum L51E31*, 1951; Harry L. Runyan, "Single-Degree-of-Freedom-Flutter Calculations for a Wing in Subsonic Potential Flow and Comparison with an Experiment," *Technical Report 1089*, 1952; and Sherman A. Clevenson, "Some Wind-Tunnel Experiments on Single-Degree-of-Freedom Flutter of Ailerons in the High Subsonic Speed Range," *Technical Note 3687*, 1956; all Washington, DC: NACA.

173 Charles H. McLellan, Thomas W. Williams, and Michael Bertram, "Investigation of a Two-Step Nozzle in an 11-Inch Hypersonic Tunnel," *Research Memorandum L9G26* (Washington, DC: NACA, 1949), pp. 4–6. The NACA republished this as unclassified *Technical Note 2171* in 1950.

174 Baals and Corliss, *Wind Tunnels of NASA*, pp. 55–56. For a more rigorous discussion of hypersonic aerodynamics, see John D. Anderson, *Hypersonic and High Temperature Gas Dynamics* (New York: McGraw-Hill, 1989, reprinted by Reston, VA: AIAA, 2000), pp. 13–23.

175 Michael J. Neufeld, *The Rocket and the Reich: Peenemünde and the Coming of the Ballistic Missile Era* (Cambridge, MA: Harvard University Press, 1995), pp. 86–88. Also Peter P. Wegener, *The Peenemünde Wind Tunnels: A Memoir* (New Haven, CT: Yale University Press, 1996, pp. 66–67.

176 Hansen, *Engineer in Charge*, pp. 344–347.

177 Ibid., p. 346.

178 McLellan, Williams, and Bertram, *Research Memorandum L9G26*, p. 21. Also Charles H. McLellan, Thomas W. Williams, and Ivan E. Beckwith, "Investigation of the Flow Through a Single-Stage, Two-Dimensional Nozzle in the Langley 11-Inch Hypersonic Tunnel," *Technical Note 2223* (Washington, DC: NACA, 1950), p. 11.

179 Baals and Corliss, *Wind Tunnels of NASA*, p. 56. For physical properties, see Ray E. Bolz and George L. Tuve, eds., *Handbook of Tables for Applied Engineering Science*, 2nd ed. (Cleveland, OH: CRC Press, 1973), p. 55.

180 McLellan, Williams, and Bertram, *Research Memorandum L9G26*, pp. 3–4. Also McLellan, Williams, and Beckwith, *Technical Note 2223*, pp. 2–3.

181 McLellan, Williams, and Bertram, *Research Memorandum L9G26*, pp. 5–6. Also McLellan, Williams, and Beckwith, *Technical Note 2223*, p. 2.

182 McLellan, Williams, and Beckwith, *Technical Note 2223*, p. 2.

183 Untitled table of projects and expenditures for Building 1229, from files maintained by Rodney Harris, NASA Langley Historic Preservation Officer. The table refers to Grant NGR-47-004-090.

184 Professors Joseph Schetz and William Devenport, conversations with author, 27 Mar. 2009.

185 Benjamin Robins is generally credited with building the first whirling arm in 1746 and using it to test the aerodynamic drag of different projectile shapes. Thomas Smeaton built the second one in 1759 to evaluate windmill sails.

186 Dimensional and performance data are from Louis W. Habel, James H. Henderson, and Mason F. Miller, "The Langley Annular Transonic Tunnel," *Technical Report 1106* (Washington, DC: NACA, 1953), pp. 1–3.

187 Ibid., p. 1.

188 The problem of wind tunnel "choking" as speed approached Mach 1 is covered more thoroughly under other tunnels, notably the Langley 8-Foot High-Speed Tunnel, so those details are not repeated here.

189 John V. Becker, *The High Speed Frontier: Case Studies of Four NACA Programs, 1920–1950* (Washington, DC: NASA, 1980), p. 80.

190 Ibid., pp. 81–82. Also Habel, Henderson, and Miller, *Technical Report 1106*, p. 4.

191 Habel, Henderson, and Miller, *Technical Report 1106*, pp. 2–3.

192 Becker, *High Speed Frontier*, p. 82.

193 *Characteristics of Nine Research Wind Tunnels of the Langley Aeronautical Laboratory* (Washington, DC: NACA, 1957), pp. 37, 42.

194 Ibid., p. 38.

195 Ibid., p. 37.

196 Ibid., p. 37.

197 Hansen, *Engineer in Charge*, p. 472.

198 Baals and Corliss, *Wind tunnels of NASA*, p. 51.

199 Bill Goode, *Infighting in the UAW: The 1946 Election and the Ascendancy of Walter Reuther* (Westport, CT: Greenwood Press, 1994), pp. 93–94. Also Baals and Corliss, Wind Tunnels of NASA, p. 51.

200 Typical reports issued during the 1950s include Lowell E. Hasel, Archibald R. Sinclair, and Clyde V. Hamilton, "Preliminary Investigation of the Drag Characteristics of the NACA RM-10 Missile at Mach Numbers of 1.40 and 1.59 in the Langley 4-Foot

Supersonic Tunnel," *Research Memorandum L52A14* (Washington, DC: NACA, 1952); M. Leroy Spearman and Cornelius Driver, "Aerodynamic Characteristics of a 0.04956-Scale Model of the Convair F-102A Airplane at Mach Numbers of 1.41, 1.61, and 2.01," *Research Memorandum SL55I22* (Washington, DC: NACA, 1955); and Cornelius Driver, "Wind-Tunnel Investigation of the Interference Effects During Separation of a 1/40-Scale Convair B-58 Airplane and Store at Mach Numbers of 1.41, 1.61, and 2.01," *Research Memorandum SL56L14* (Washington, DC: NACA, 1956). Also Baals and Corliss, *Wind Tunnels of NASA*, p. 51.

201 Harry W. Carlson and Barrett L. Shrout, "Wind-Tunnel Investigation of the Sonic-Boom Characteristics of Three Proposed Supersonic Transport Configurations," *Technical Memorandum X-889* (Washington, DC: NASA, 1963). Also Baals and Corliss, *Wind Tunnels of NASA*, pp. 111–112.

202 R. D. Launius, T. B. Irvine, and E. A. Arrington, "NACA/NASA and the National Unitary Wind Tunnel Plan, 1945–1965" (Reston, VA: AIAA, 2002), pp. 7, 18.

203 Baals and Corliss, *Wind Tunnels of NASA*, pp. 113–114, 133–134. Also Hansen, *Engineer in Charge*, p. 472.

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The National Full-Scale Aerodynamics Complex in the foreground and Hangar 1 in the background dominate this aerial view of Ames Research Center. The grassy area at right with several red-tile-roofed buildings and Hangar 1 is the Navy's original Moffett Field dirigible base and now a historic area. (Photo credit: NASA AC82-0465-2.1)

AMES RESEARCH CENTER

Joseph S. Ames
(Photo credit: NASA LAL-90-3738)

By 1937, the NACA realized that it needed to expand beyond its Langley Laboratory in Hampton, Virginia, and the Committee began to investigate possible locations for a second laboratory. At the same time, it also began to lay the groundwork necessary to gain congressional support for such an expansion. The burgeoning aircraft manufacturing industry along the West Coast led the Committee to favor a western location for any new facility. Since the airline industry was in its infancy and travel across the country by train took about three days, a western laboratory would be more convenient and responsive to the research needs of those companies than other locations. But as congressional support for the second laboratory grew, so did the desires of several influential legislators to have it located in their districts. This led to an extensive series of investigations during 1939 that compared several prospective sites around the country. Ultimately, Congress voted to authorize the new laboratory, and the NACA selected Moffett Field, an underutilized Navy dirigible base at Mountain View, California, for its location.[1]

Construction of three wind tunnels began immediately, and plans for others started to take shape as well. In 1940, the NACA decided to name the laboratory for its recently retired Chairman, Joseph S. Ames, and its first two wind tunnels opened in 1941. Additional tunnels, including the 40- by 80-Foot Full-Scale Tunnel (now part of the National Full-Scale Aerodynamics Complex), opened during World War II and contributed significantly to the war effort.

The NACA originally intended for Ames to concentrate on aeronautical and airframe research, with an eye toward higher-speed flight in the future. After the war and the introduction of jet engines, the era of supersonic flight began, and this mission intensified. With Cold War–era funding from Congress, engineers and researchers at Ames built and used a growing collection of supersonic and transonic tunnels to rapidly advance the state of the art in aeronautics. With the beginning of space exploration and the creation of NASA in 1958, aeronautics research at the renamed Ames Research Center expanded beyond atmospheric flight and further into the realm of hypersonics, building hypervelocity tunnels and exploring the problems of entering the atmospheres of planets beyond Earth. For several of these facilities, Ames engineers had to devise entirely new concepts for tunnel design and operation. These exotic facilities hosted research during the next three decades that was essential to the success of numerous planetary probes. During this same period, improvements to Ames's most productive conventional wind tunnels kept them modern and attractive to outside customers and NASA researchers.

Reductions in congressional support for aerospace research and significant changes in the aerospace industry during the 1990s led to a substantial reduction in test programs at Ames—and the other NASA centers as well—that forced the agency to mothball or close a number of its tunnels. Ames was particularly hard hit, but the center branched out into new areas of research in the 1990s, such as establishing astrobiology at NASA and becoming the agency's Center of Excellence for Information Technology.

Today, in addition to its aerodynamic roots, core areas of expertise at Ames include entry systems, advanced computing and IT systems, air traffic management, astrobiology and life science, cost-effective space missions, intelligent and adaptive systems, and space and Earth science.

7- BY 10-FOOT WIND TUNNEL NUMBER 1
7- BY 10-FOOT WIND TUNNEL NUMBER 2

This 1977 aerial view shows the dual 7- by 10-Foot Wind Tunnels about 1980, with No. 1 at the top and No. 2 toward the bottom. The rectangular structure next to No. 1's air-exchange tower is the rotor test apparatus. Two metal shop buildings are also visible. (Photo credit: NASA AC77-0846-015)

SIGNIFICANCE

The two 7-by 10-Foot Wind Tunnels, Number 1 (7- by 10-Foot No. 1) and Number 2 (7- by 10-Foot No. 2), were the first wind tunnels put into operation at the Ames Aeronautical Laboratory. Opened in April and August 1941 respectively, they were essentially identical tunnels built to perform a variety of basic aeronautical tests in an economical and expeditious manner. Both tunnels saw heavy use during World War II and the following decades, particularly for tests involving stability and control issues, and both later hosted basic rotor blade testing under a unique operating agreement between NASA and the U.S. Army.

DESCRIPTION

Since these two wind tunnels were originally identical and remain very similar, this description applies to both, unless specifically noted otherwise. The 7- by 10-foot tunnels at Ames were based on the successful design of the Langley Laboratory's 7- by 10-Foot Atmospheric Wind Tunnel (7- by 10-Foot AWT), which had opened in 1930 and been modified with a closed test section in 1938, but they also benefited from design studies

under way at Langley for a pair of new 7- by 10-foot tunnels there. Though the Langley tunnels would open later, they and the two 7- by 10-foot tunnels at Ames bore many similarities. None broke much in the way of new ground in wind tunnel design, but they entered service as modern tunnels with proven design elements, including the closed circuit and test section with a single-return duct, an externally braced steel shell, a variable-speed electric motor driving an airfoil-bladed fan, air-exchange for temperature control, a six-component balance, and multitube manometers for pressure measurements around the test model. The mechanical instrumentation was later replaced with electronic devices.

As the first wind tunnels at Ames, the 7- by 10-foot tunnels' location became the core around which the remainder of the laboratory grew. They were built on the eastern half of a plot two blocks north of the Navy's original Moffett Field campus. Built parallel to one another on an east-west orientation, 7- by 10-Foot No. 1 (Building N-215) is south of 7- by 10-Foot No. 2 (Building N-216). The 16-Foot High-Speed Tunnel, later converted into the 14-Foot Transonic Tunnel, occupied the western half of this block until its demolition in 2009.

Designed as atmospheric tunnels, each 7- by 10-foot tunnel employs a rectangular cross section throughout its circuit, except for transitions into and out of its fan. Without pressurization, the more difficult and expensive-to-build circular section was unnecessary. Overall, each tunnel measures approximately 228 by 85 feet in plan. Their cross sections gradually increase through the circuits, from 7 feet high by 10 feet wide in each test section to 30- by 33-foot settling chambers.[2]

A variable-speed, 1,800-horsepower electric motor driving a single, 28-foot-diameter, fixed-pitch fan powers each tunnel, with the motor enclosed in a nacelle. This combination provides a 0- to 250-mph speed range in the test section. Countervanes immediately after the fan minimize any swirl induced by the fan. Heat introduced by the motor and fan is dissipated through an air exchange tower downstream from the fan that continuously exchanges a small fraction of tunnel air for cooler outside air. This tower uses the changing static pressure of the air flowing through it to drive the air exchange without a need for auxiliary fans. The tunnels' internal temperatures are not controlled and typically run about 120°F during operation.

Each test section is 16 feet long, with side doors opening to 6 feet, 4 inches by 10 feet and a ceiling hatch for model installation and servicing. The ceiling hatches vary in the two tunnels, with No. 1's hatch measuring 4 feet, 6 inches by 5 feet, and No. 2's hatch being 4 feet, 9.5 inches in diameter. Each test section is enclosed in a cubical structure approximately 44 feet on each side. Airplane models are mounted on stings or vertical struts, and two-dimensional mountings between floor and ceiling accommodate airfoils.

Instrumentation in the two tunnels was very similar. Each originally employed mechanical balances, but these were replaced with electric strain-gages, probably during the 1970s. The sting supports a six-component balance, and the two-dimensional mounting contains a three-component balance. Angle of attack and yaw can be dynamically

varied to suit the test program. Both tunnels have a 360-degree yaw capability and a ±45-degree pitch range using their sting mounts. Mounting an airfoil vertically on either of the turntables allows its angle of attack to be varied between 0 and 180 degrees. A variety of temperature and pressure measurements can also be recorded, with up to 576 data channels simultaneously monitored. Variable-frequency electric drives and a 3,000-psi air supply are available to power models as needed. By the early 1980s, both tunnels were equipped with laser doppler velocimetry systems.

A rotor test building adjoins the 7- by 10-Foot No. 1's northwest corner, though it is not actually a part of either wind tunnel. The Army built this cubical, reinforced concrete structure about 1972 to test models of complete rotor assemblies under rotation. The heavy construction was to minimize damage in the event of a rotor failure. The test cell was acoustically lined, and it featured a movable platform to prevent rotor wake reingestion.

A two-story masonry building on the 7- by 10-Foot No. 1's south side originally provided office and some shop space for both of the 7- by 10-foot tunnels, supported by a smaller, single-story masonry shop building on the 7- by 10-Foot No. 2's south side and two additional metal shop buildings nearby. While some wind tunnel offices remain in Building N-215, a portion of the building is now occupied by the center's medical clinic, which has an independent entry on the west end of the building.[3]

HISTORY

The 7- by 10-foot tunnels were born out of necessity. The NACA's 7- by 10-Foot AWT at Langley had been the setting for a variety of test programs since its opening in 1930, and its size had proven to be a very practical one that matched the general height-to-width proportions of monoplanes well. Clearances in both directions allowed for investigations involving vertical and lateral forces without undue wall effects, and its six-component balance measured forces and moments along and about an airplane's three axes, giving engineers comprehensive sets of data. As aircraft speed increased rapidly throughout the 1930s, the tunnel's 80-mile-per-hour top speed began to limit tests to takeoff and landing performance. Accordingly, the 7- by 10-Foot AWT saw several systematic investigations of high-lift devices and systems, many of which focused on the plane's stability and control characteristics with such devices deployed. At least 50 different aircraft models benefited from testing in the tunnel.[4]

The threat of World War II further increased the number and developmental pace of new military aircraft. Since most of these designs were pushing the new technologies developed during the 1930s further, the demand for test time in wind tunnels ballooned, pushing Langley's capabilities to the limit. Rear Admiral Arthur Cook and Captain Walter Diehl of the Navy's Bureau of Aeronautics had been studying the growing problem since 1936 as part of the Bureau's Special Committee on Future Research Facilities. In December 1938, the committee recommended that the NACA launch a major expansion effort, including a second aeronautical laboratory and several new

facilities at Langley. Already aware of the need, as well as the cost, the NACA used the committee's report to justify a request for funds to Congress. In 1939, Congress finally approved funds for the new laboratory, specifying Moffett Field in Mountain View, California. The NACA began planning and design work immediately.[5]

Langley engineers Smith J. "Smitty" DeFrance and John Parsons led the team charged with building the new laboratory and its first wind tunnels, but much of the detailed design work was done by other engineers like H. Julian "Harvey" Allen, Carlton Bioletti, and Harry Goett, who moved from Langley, and by newly hired engineers from the area, such as Walter Vincenti. (Vincenti, a then recent Stanford graduate, was DeFrance's first local hire, and he enjoyed a long and distinguished career at Ames.)[6]

The original intent for the new and as yet unnamed laboratory was research into high-speed flight, and a 16-foot high-speed tunnel was to be its initial facility, but the priorities of the U.S. military altered these plans somewhat. Believing America's entry into World War II to be just over the horizon, the Army and the Navy wanted wind tunnels to test and refine designs then in progress, and they wanted these tunnels quickly. Once Congress had funded the new West Coast laboratory, the services lobbied the NACA to solve their problem. Thus, design and construction of two 7- by 10-foot tunnels progressed simultaneously alongside the 16-Foot High-Speed Tunnel.[7]

Construction of the 7- by 10-Foot No. 1 began in May 1940 and proceeded rapidly. Less than a year later, the tunnel entered service in April 1941. Construction of the 7- by 10-Foot No. 2 followed closely behind, beginning in August 1940 with completion in August 1941. Each tunnel began to test models of military airplanes as soon as it could be calibrated and placed into service. These models, which could have wingspans of up to 8 feet, were built for straight-forward aerodynamic testing at speeds of up to approximately 250 mph, so they could be constructed from wood and modified easily. Thus, test programs could proceed rapidly and economically, and some of the American aircraft flown immediately after Pearl Harbor had already benefited from these tests. Subsequent designs benefited as well. Even planes with top speeds well above what these tunnels could generate saw low-speed testing in the tunnel. For the Navy, which operated planes close to their stall speeds onto and off of aircraft carriers, low-speed testing of stability and control characteristics was particularly crucial. Engineer-in-Charge DeFrance appointed Harry Goett as the first section head over both of the 7- by 10-foot tunnels, and he soon became the leading figure in low-speed research at Ames.[8]

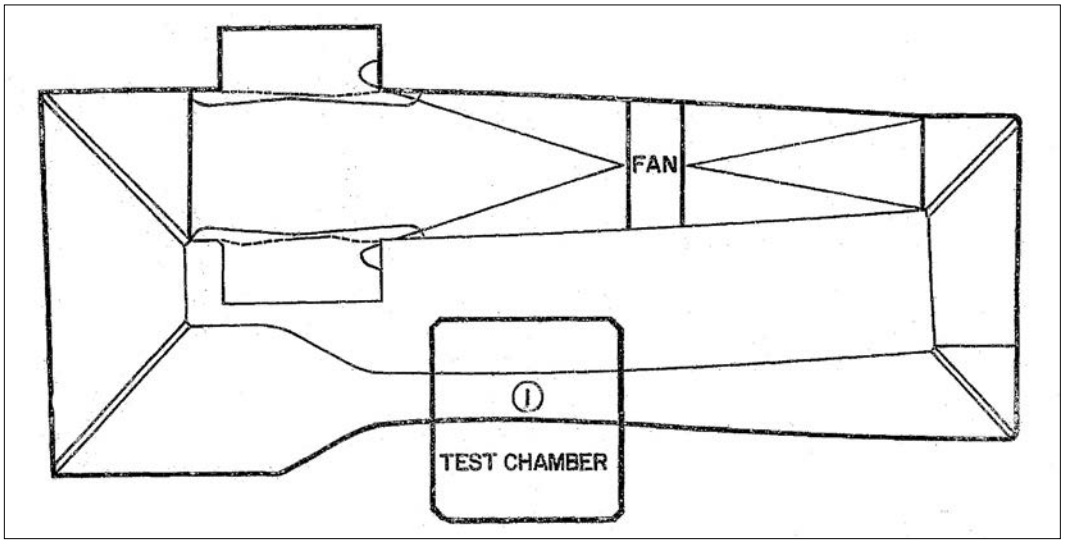
The dual 7- by 10-foot tunnels proved to be workhorses at Ames, and they hosted a wide variety of test programs over the years, many of which involved aircraft stability and control characteristics. While they retained their original configuration and performance specifications, engineers installed improved instrumentation and made some modifications over the years. Electronic instrumentation replaced the mechanical devices, and electronic data acquisition equipment was added. By 1982, the tunnels featured laser doppler velocimetry systems for nonintrusive studies of localized airflows, and portions of the test section and diffuser in No. 1 had received removable test section

sidewalls and acoustic panels to minimize ambient noise, giving that tunnel the ability to host aeroacoustic tests. Tunnel No. 1 also had its remaining asbestos-cement panels removed, probably when its test section walls were modified. Additionally, both tunnels had received gust generators, making them more-versatile facilities for low-speed stability and control testing.[9]

By 1965, a declining demand for low-speed wind tunnel research from outside customers and Ames researchers led NASA to consider closing the two 7- by 10-foot tunnels, but the U.S. Army intervened. These tunnels were good venues for testing new concepts of rotor blades for helicopters and other vertical takeoff aircraft, and the Army did not want to lose the capability. This led to an unusual operating agreement between NASA and the Army where the Army Air Mobility Research and Development Laboratory at Ames became the Aeroflightdynamics Directorate (AFDD), a pseudo-NASA directorate. The AFDD employed both NASA and Army personnel to operate the 7- by 10-Foot No. 2, and it functioned as a NASA unit. NASA continued to operate the 7- by 10-Foot No. 1 as part of the Fluid Mechanics Lab.[10]

The two 7- by 10-foot tunnels continued in active service, but No. 1 gradually became the primary tunnel. No. 2 fell largely into disuse, and it was closed in 1993. During one contractor program in 1997, an accident damaged turning vanes in the No. 1 tunnel, and turning vanes from No. 2 were salvaged to replace the damaged ones. In 2006, Ames decided to terminate the existing agreement with the Army. Since that time, the Army has leased the 7- by 10-Foot No. 1 from NASA, who retains full ownership.[11]

These two tunnels have served the NACA, NASA, and the Army for half a century, and the 7- by 10-Foot No. 1 remains in service. Although some components had been removed, the 7- by 10-Foot No. 2 sat unused, but largely intact, for a number of years prior to its demolition.



This plan drawing shows the general arrangement and major dimensions of the two 7- by 10-foot wind tunnels when built. Both tunnels have retained this configuration. (Image credit: NASA TM-X73134, Fig. 1a)

These views in the 7- by 10-foot test sections show a 1942 XSB2D-1 model (top) and an airfoil (bottom) set up for testing. The struts supporting the XSB2D-1 are mounted on a six-component balance below the floor. The L-shaped probe behind the airfoil measures pressures in the flow field leaving the airfoil. Note the turntable in the floor. NACA and NASA test reports often did not specify which of the two 7- by 10-foot tunnels had been used for a particular test program, and the specific tunnel(s) in these photographs is unknown. (Photo credits: NASA AAL-1443 and NASA AAL-1986)

16-FOOT HIGH-SPEED TUNNEL
14-FOOT TRANSONIC TUNNEL

The 16-Foot High-Speed Tunnel in 1942, shortly after it entered service as the third wind tunnel at the young laboratory. The two 7- by 10-foot tunnels and a hangar are on the right. (Photo credit: NASA A-12679)

SIGNIFICANCE

The 16-Foot High-Speed Tunnel (16-Foot HST) was the third wind tunnel built at Ames and the next-to-last American wind tunnel to enter service before the nation's involvement in World War II. It also was the most powerful wind tunnel built up to that time. During the war, it was the site of test programs that helped solve serious problems caused by compressibility and boundary layer turbulence in high-speed airplanes with localized flows approaching the speed of sound. A major rebuilding into the 14-Foot Transonic Tunnel (14-Foot TT) made it Ames's first large wind tunnel with ventilated walls for stable transonic operation. The tunnel was routinely upgraded, and it performed extensive aircraft and some spacecraft aerodynamic testing for over four decades.

DESCRIPTION

Originally built as the 16-Foot HST in 1941, the 14-Foot TT was a large, closed-circuit, externally braced, steel wind tunnel. Its rebuilding into the 14-Foot TT in 1955 added longitudinal members between the original structural rings that gave most of the tunnel a distinctive, honeycomb-like appearance. A two-story masonry building on the tunnel's

south side housed offices and model-preparation shops. A 30- by 40-foot-wide high-bay area rose another 20 feet above the roof at the back center of the building. An equally tall, cubical test-section enclosure joined the office building at this location.

As built, the 16-Foot HST measured approximately 170 feet by 500 feet in plan, plus the office and air-exchange tower and motor room footprints. This air-exchange tower, which replaced some of the tunnel's air with outside air to remove internal heat generated by the motor and fan, rose above the tunnel approximately 60 feet ahead of Corner 3. This tower, constructed with an external steel frame and corrugated-asbestos-cement-board sheathing, had inlet grills around its upper sides and a roof exhaust. During conversion to the 14-Foot TT, the original air exchange tower was removed and replaced by a larger tower of different design. Where the old tower had straddled the tunnel, the new one, with its separate intake and exhaust sections, stood beside the tunnel immediately ahead of Corner 3, connected to it by horizontal ducts within an enclosure. Approximately 55 by 135 feet in plan and 110 feet high, it featured an exhaust grill through the roof of the exhaust section and intake louvers on the three exposed sides of the intake section. A room at its base enclosed electrical equipment. Because of the tunnel's 70-foot-diameter settling chamber, its centerline was approximately 40 feet above the ground throughout the circuit. This centerline height was retained during the 1955 rebuilding. The circuit measured approximately 1,080 feet along its centerline. The four corners were mitered and equipped with turning vanes to help maintain stable, non-stratified flow. Twelve of the structural rings conveyed the tunnel's weight to steel support columns that in turn rested on concrete foundations. The fan and motor sections were supported on concrete pedestals. To minimize solar heat gain, the steel portions of the tunnel were painted silver.[12]

The original test section was 16 feet in diameter with a closed throat, but this was replaced in 1955 with one measuring 13 feet, 6 inches by 13 feet, 8.5 inches at its entrance. This test section included ventilated walls and a surrounding plenum, along with an exterior support structure. The ventilated walls contained slots open to the plenum for transonic operation, but they were a constant width with corrugated inserts, not the contoured slots previously used at Langley. Engineers at Ames had proven the ventilated-wall design in the 2- by 2-Foot Transonic Tunnel that they built for that purpose, and it worked well in the renamed 14-Foot TT, too. Between many of these slots were optically clear windows suitable for schlieren photography. The inlet nozzle featured flexible walls developed by H. J. "Harvey" Allen, an Ames addition to Langley's fixed-transonic-throat design. Allen's idea used a single jack to adjust each of the walls and reduce shock wave reflection. Allen had previously built a 5- by 5-inch pilot nozzle to validate his idea and then installed a flexible nozzle in the 2- by 2-Foot Transonic Tunnel.[13]

The original design located two 14,000-horsepower drive motors in tandem on a pedestal in an external housing on the north side of Corner 2. They turned a single fan housed in a nacelle between Corners 1 and 2. This basic arrangement was retained, but enlarged, during the 1955 rebuilding. The old motors were exchanged for three new, variable-speed motors delivering a total of 110,000 horsepower, and a three-stage axial

compressor replaced the single fan. The installation included a new streamlined fairing around the compressor shaft and hubs and new concrete pedestals.

As in most modern wind tunnels, the 14-Foot TT's cross-sectional dimensions gradually increased from approximately 14 by 14 feet at the test section to diameters of 45 feet in the fan section and, ultimately, 70 feet in the settling chamber. This yielded a 20.8:1 contraction ratio into the test section. Unlike the 16-Foot HST at Langley, which required a substantial lengthening of its diffuser to efficiently handle transonic speeds, the Ames 16-Foot HST was built with a diffuser designed for Mach 1, and its circuit needed no major alterations during its conversion for transonic operation.

Instrumentation varied over the tunnel's life, but it was always tailored to the tunnel's mission of basic aerodynamic testing. The original mechanical balance held models in the 16-Foot HST on three suppor80t struts that were mounted on the balance frame. A system of rods and levers conveyed the aeronautical forces to seven scales below the test section that yielded forces and moments in all directions. A sidewall mounting arrangement used vertical turntables to vary the model's pitch as desired, and a sting was added later. It utilized a vertical blade with two movable bars downstream of the test section. The sting, attached to the movable bars, extended upstream to support the model in the center of the test section. A motor-driven lag screw moved the two bars vertically to adjustment pitch while keeping the model properly centered. Pressure taps on the model connected to multitube manometers furnished pressure data. Photographs of the manometers taken during test runs were later examined by technicians who recorded the data for each tap manually.

By the 1955 rebuilding, strain gage–based balances and sting mounts had become the preferred model support system for most tests, and the new test section included them, along with pressure transducers to replace the manometers by feeding electric signals to data acquisition equipment. A schlieren photography system was installed, and later modifications added computer-based data acquisition and control systems, increasingly capable sensors, and new techniques such as laser doppler velocimetry.[14]

HISTORY

As noted in the section about the 7- by 10- Foot Wind Tunnels, European nations were pursuing aviation research more actively than the United States during the late 1930s. Although an isolationist Congress was slow to respond, the NACA finally secured $11 million for new facilities in 1939. The largest portion of these funds allowed the NACA to begin construction of a new West Coast facility. The committee named it the Ames Aeronautical Laboratory about a year later.[15]

Smith J. "Smitty" DeFrance and John Parsons, who transferred to California from Langley, assembled and led the team charged with building the new laboratory and its first wind tunnels. Various members of this team did most of the detailed design work on the tunnels, though DeFrance's influence was substantial. With his extensive experience in large wind tunnels, DeFrance's recommendations were sound and generally

welcome. The team DeFrance and Parsons assembled, which was built around several Langley engineers and supplemented by others from the local area, proved to be up to the task, and they would continue to dominate tunnel design and innovation at Ames for many years. They were also researchers at heart, and DeFrance took pains to keep their research interests alive during the initial construction period.[16]

The original intent for the new laboratory was research into high-speed flight, and the 16-Foot HST was to be its initial facility, but the priorities of the U.S. military altered these plans somewhat. Believing America's entry into World War II to be imminent, the Army and the Navy wanted and needed some basic wind tunnels to test and refine airplane designs then in progress. Once Congress had funded the new West Coast laboratory, the services lobbied the NACA to build simple tunnels they could quickly use. Thus, the team broke ground for the first of two 7- by 10-foot wind tunnels and the 16-Foot HST in May 1940, and construction of all three tunnels progressed simultaneously.[17]

Being much more complex than the smaller tunnels, the 16-Foot HST took longer to complete, but its construction proceeded rapidly nonetheless, and the tunnel first ran on 22 August 1941. At completion, DeFrance put Manley Hood, one of the transfers from Langley who had done much of the design work on the tunnel, in charge of its operation as well. As expected, the checkout and calibration of this tunnel presented some new challenges, and DeFrance wanted one of his most experienced engineers in charge. (Hood would later assume a similar role at the 40- by 80-Foot Full-Scale Tunnel.) Checkout and calibration took almost a year to complete, but Hood was able to schedule some testing during this period after the worst problems were solved. One serious problem involved the compressor support struts and countervanes intended to remove airflow swirl from the compressor blades. Instead of removing the swirl, they actually generated additional disturbance, and a major redesign was needed to solve the flow problems.[18]

As expected, the tunnel would generate speeds of up to Mach 1 with nothing in the test section but suddenly "choke" at that speed. No increase in power would produce a higher speed, and adding a model and support struts reduced the choking speed to as low as Mach 0.7. Researchers had a poor understanding of the problem, but they learned much by modifying the struts to reduce the blockage and raise the choking speed, making the tunnel capable of achieving test speeds approaching Mach 0.9.[19]

A less serious, but initially frustrating, problem required no physical change to fix. The calibration process occurred during the early months of World War II, and Ames was part of Moffett Field, an active Army base at the time. The Army feared that the Japanese might attack it from the air just as they had Pearl Harbor. As luck would have it, the 16-Foot HST unexpectedly emitted a low-pitched rumble when running that sounded rather like a squadron of approaching airplanes. When the engineers ran the tunnel late at night, the Army guards heard the rumble, sounded an air-raid alarm, and, in accordance with established procedures, ordered all large facilities, including the tunnel, to shut down immediately. To their relief, the rumble disappeared, indicating a false alarm, and they restored normal operations. When the tunnel restarted, the

rumble returned, and the guards again sounded the alarm! As before, the "airplanes" went away. It took several of these cycles before someone made the connection and resolved the issue. In actuality, the Japanese never came close to attacking Moffett Field.[20]

Once in service, the 16-Foot HST proved its worth in short order, and it was soon booked around the clock. Several of its wartime test projects made vital contributions to military aircraft that became legendary during the war, including the P-38 Lightning, P-47 Thunderbolt, and P-51 Mustang, to name a few. The P-38 was the first American fighter fast enough to experience serious compressibility problems. During high-speed dives, local shocks and pressure changes at the horizontal stabilizer caused the dive angle to increase and make it virtually impossible for the pilot to pull out of the dive. Builder Lockheed and Langley engineers had developed a conceptual fix that used small flaps on the underside of the wings, but the concept had to be proven. The 16-Foot HST team did this validation work, as well as determining the correct size for the flaps. The simple, inexpensive fix gave P-38 pilots a safe way to avoid or recover from the usually fatal dives. Similar dive flaps became standard on other high-performance fighters, like the P-39, P-47, and P-51, as well, and investigations into the high-speed characteristics of such airplanes continued throughout the war.[21]

The P-51, one of the most aerodynamically advanced propeller-driven aircraft ever built, also benefited from testing in the 16-Foot HST. The prototype XP-51 performed very well, but it had a worrisome vibration in flight. The 16-Foot HST team removed the outer portions of its wings and mounted it in the tunnel, where test runs quickly allowed them to determine that the vibration emanated from a novel, ventral air scoop for the engine's radiator. Wanting an aerodynamically clean design, the builder had placed the scoop so close to the fuselage that its edge was within the turbulent boundary layer. Lowering the scoop to put it just outside the boundary layer solved the problem. Tests in the tunnel resulted in similar detail improvements in several aircraft produced during the war.[22]

An unexpected disaster befell the 16-Foot HST in December 1943 when one of the two main drive motors burned out during a run. With the demands on the tunnel, a rapid repair was essential, despite the holiday season. Ames engineers and technicians, along with those from General Electric, the motor's builder, worked around the clock and through the Christmas and New Year holidays to remove, rewind, and reinstall the motor. Amazingly, the tunnel was out of service for only one month, thanks to their dedicated efforts.[23]

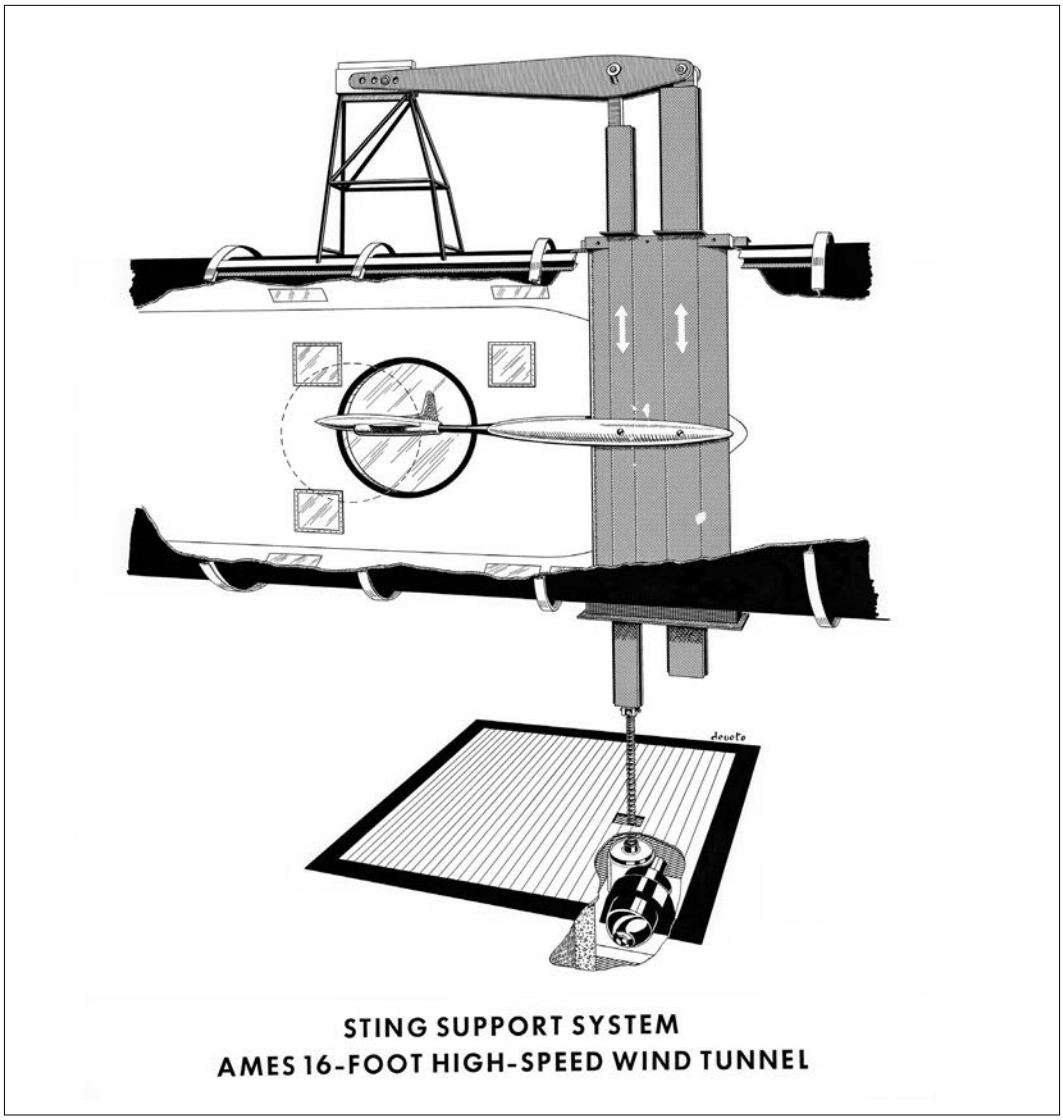
With the advent of jets after World War II, transonic (generally defined as being between Mach 0.7 and 1.2) research suddenly became a top priority. As discussed above, and in the Langley 8-Foot High-Speed Tunnel listing, choking problems prevented stable wind-tunnel operation near the speed of sound until Langley's Ray Wright developed a practical slotted-wall design in 1950. It was installed in Langley's rebuilt and renamed 16-Foot Transonic Tunnel, but the contoured slot design was less than perfect. Once the slot problems were resolved, the rebuilt tunnel soon became a well-utilized facility.[24]

By 1953, many at Ames felt that a similar conversion of the 16-Foot HST would yield similar results, but that feeling was far from unanimous. Some prominent researchers, such as Carlton Bioletti, believed the 2- by 2-Foot TT and the 11- by 11-foot transonic portion of the Unitary Plan Wind Tunnel, then under construction, would provide sufficient transonic testing capability. But transonic research was a hot topic at the time, and Ames engineers believed they had developed a couple of improvements—a different slot design and an adjustable nozzle—that would make their tunnel better than Langley's. The proponents succeeded in obtaining $9 million, 4.5 times the tunnel's original cost, to make the conversion, which began in 1951.[25]

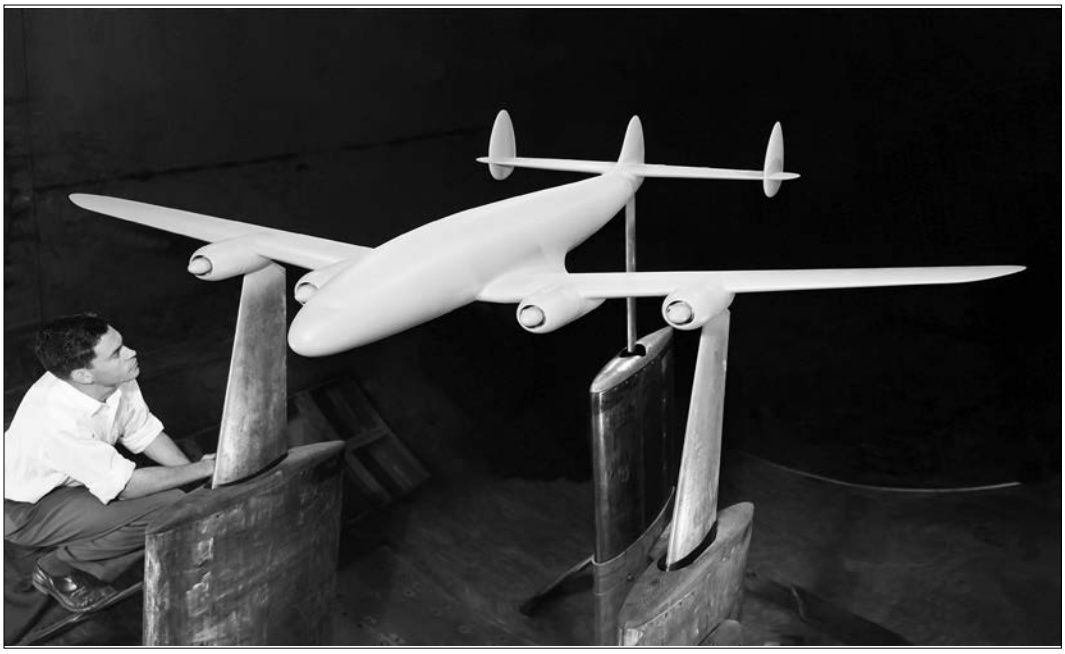
The rebuilt and renamed 14-Foot Transonic Tunnel opened in 1955 with a continuously variable speed range of Mach 0.6 to 1.2, thanks in part to the flexible-wall nozzle. It remained an atmospheric tunnel, but the new air-exchange tower provided some active control over the operating temperature, which was normally about 180°F. Researchers rapidly booked the 14-Foot TT with a wide variety of test programs, particularly programs involving jet engine inlets and exhausts, and their interactions with the airframes. They learned much about how the shape and configuration of these penetrations affected the performance of both engines and aircraft. This research built upon work begun during the late 1940s that had already produced the famous "submerged inlet" design that both improved inlet performance and reduced drag in many situations, and it continued well into the NASA era.[26]

The NASA era introduced some new concepts in spacecraft and airplane design that were evaluated in the 14-Foot TT. One of the more unusual ones was Harvey Allen's oblique wing, a single-piece wing that rotated horizontally about its center to change sweep, with one side moving aft and the other forward. Tests in the 14-Foot TT validated the concept, and a research airplane confirmed it, but the design was too unorthodox for any manufacturer to adopt it for a production airplane.[27] The 14-foot tunnel was also used to test a scale model of the Stratospheric Observatory for Infrared Astronomy (SOFIA) for over 100 hours in an effort to minimize the optical distortion as air flowed over the telescope's open door in the aircraft's fuselage; to study the high-speed, open-rotor concept; and to test high-pressure air-powered turbine-powered simulator units.[28]

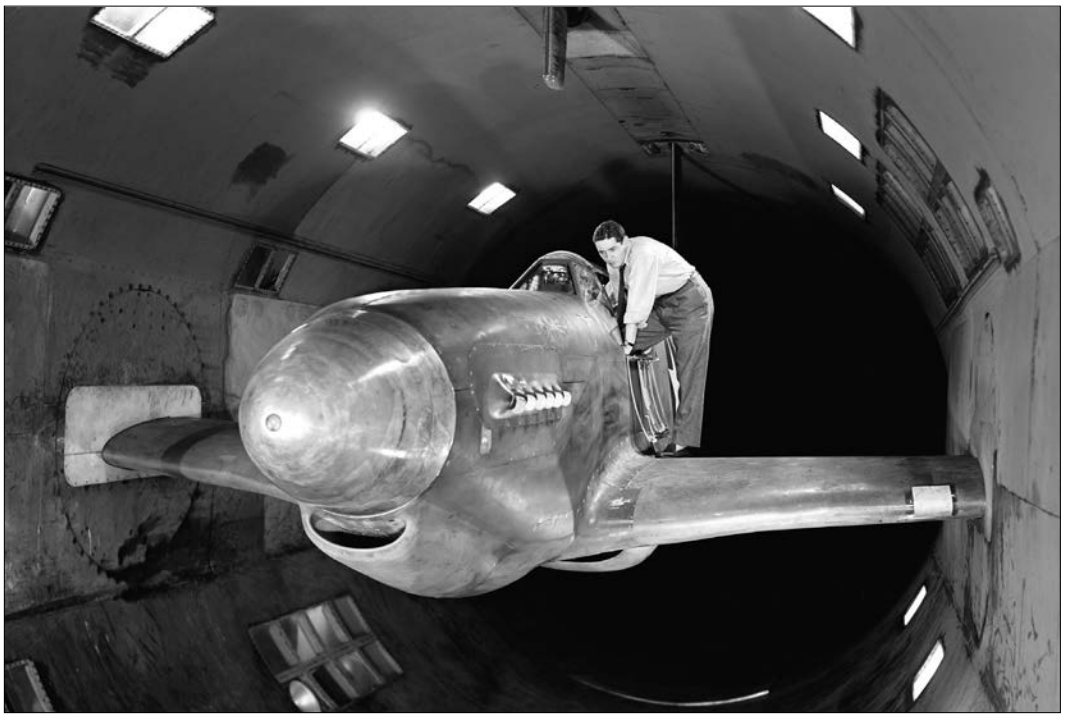
While the 16-Foot HST and 14-Foot TT had hosted a wide variety of important test programs for decades, changes in the aviation industry gradually reduced the tunnel's workload during the 1960s and again in the 1990s. An overall reduction in the number of new aircraft development programs reduced the demand for testing, as did the changing nature of aeronautical research, including the growth of computational fluid dynamics (CFD). These factors, coupled with budget constraints and the availability of other tunnels with similar capabilities, led NASA to mothball the 14-Foot TT in 1997. It was never restarted, and NASA demolished it in 2009. No portion of the tunnel is known to survive.



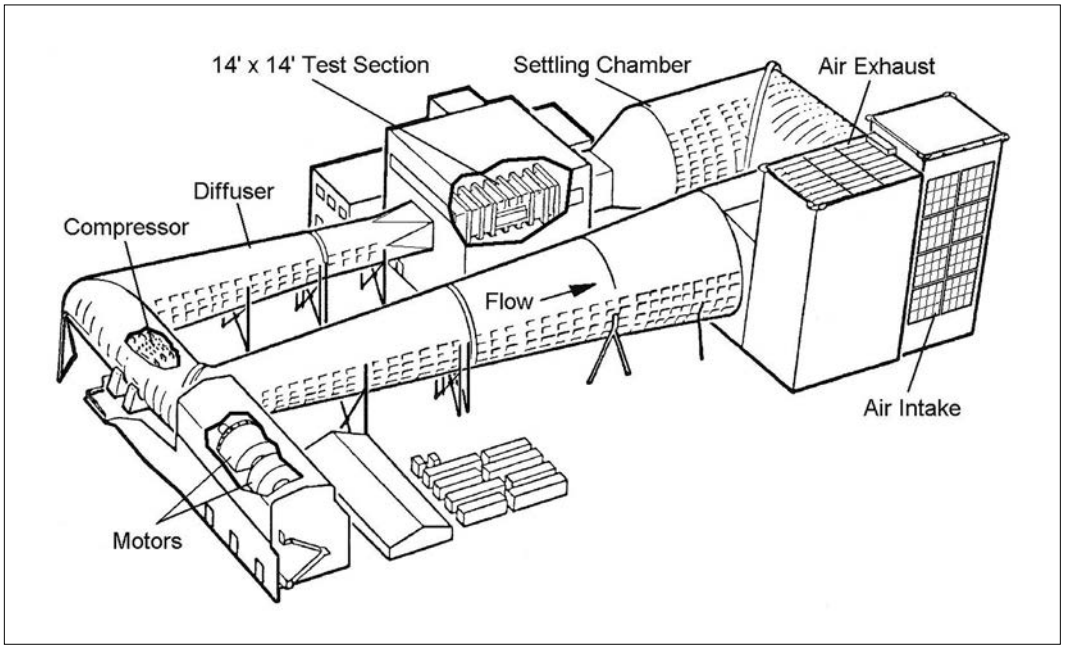
This drawing shows how the 16-Foot High-Speed Tunnel's original sting mount functioned to adjust pitch while keeping the model centered in the test section. The gearmotor at the bottom moved the left bar, and the upper lever moved the right bar a greater distance in the same direction, causing the sting to rotate and change angle. Since the model was directly under the upper lever's fulcrum, it rotated in place. (Image credit: NASA A-12107)



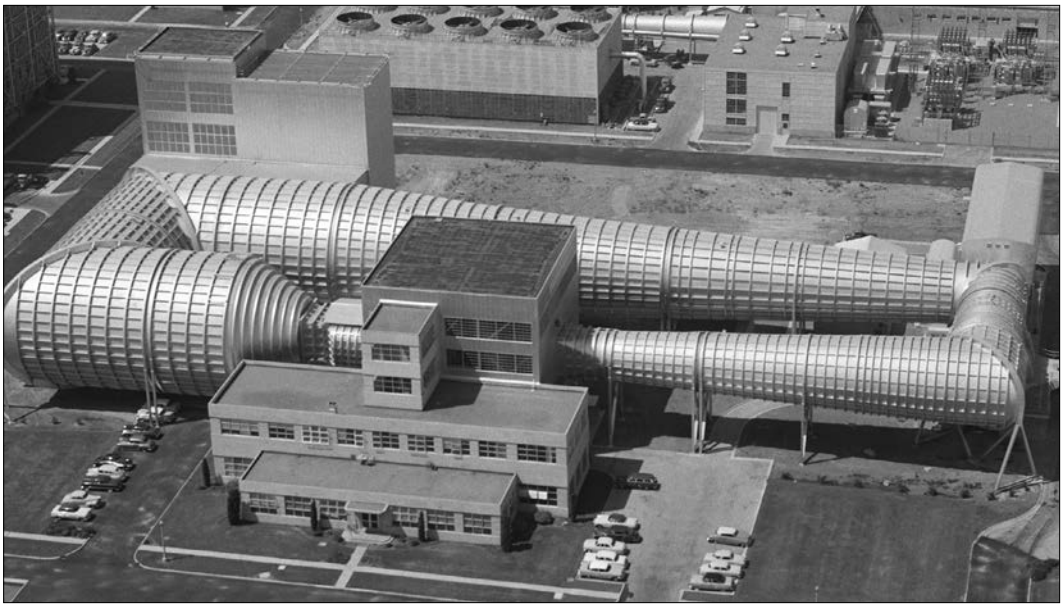
These two photographs show how the test section and model mounting changed from the 16-Foot High-Speed Tunnel (top) to the 14-Foot Transonic Tunnel (bottom). The L-069 Constellation is supported on three streamlined struts attached to the mechanical balance in 1942, while the conical cambered wing model in 1959 in the 14-Foot TT is sting-mounted with internal strain-gages. Note the numerous windows and lights between the slots of the 14-Foot TT's test section. (Photo credits: NASA AAL-2955 and NASA A-24776)



By testing an XP-51 with cropped wings in the 16-Foot High-Speed Tunnel in 1943, Ames researchers traced the source of a serious rumble to the location of the plane's air scoop below the fuselage. The problem scoop is barely visible below the wing. Note the turntables in the walls for pitch adjustment. (Photo credit: NASA AAL-3782)



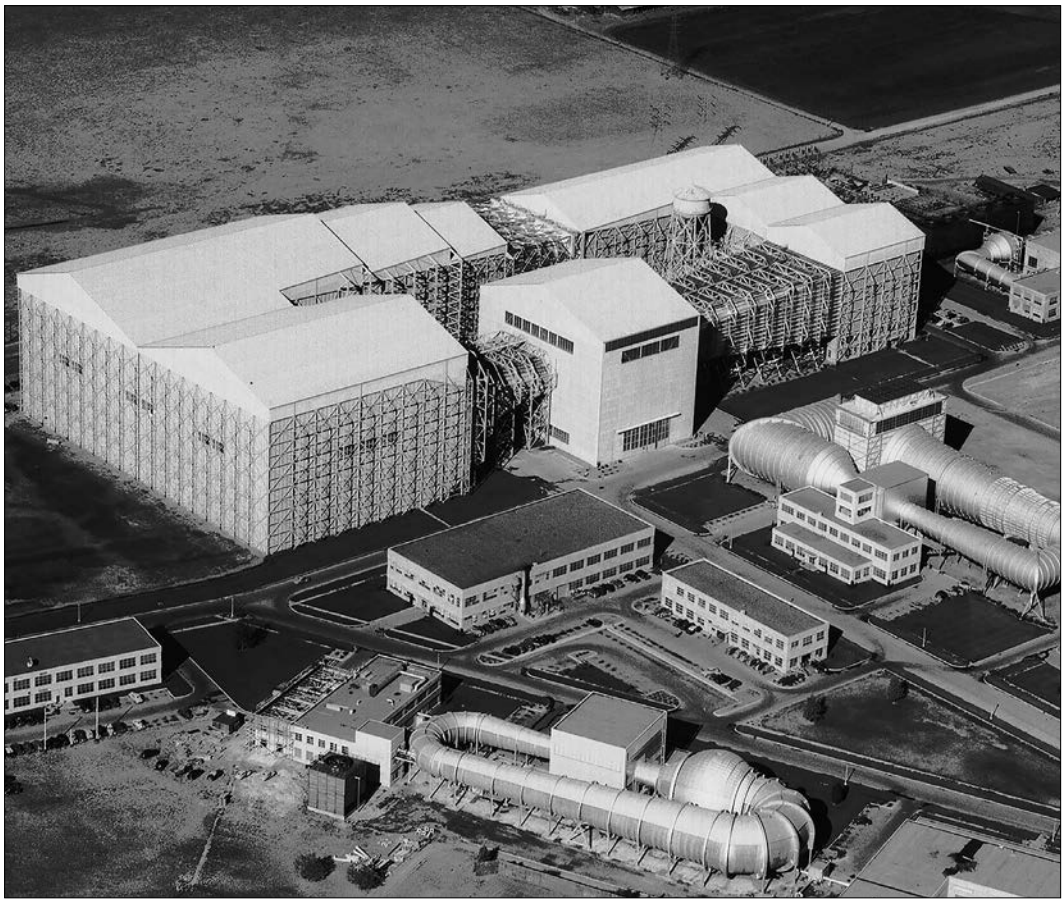
This cutaway drawing of the 14-Foot Transonic Tunnel is partially cut away and labeled to reveal and identify its major components. The most complex portion of the tunnel was its test section. Entering air flowed through the flexible-wall nozzle before entering the ventilated test section and finally passing the sting support as it exited to the tunnel's diffuser. (Image credit: NASA A-20621)



This 1955 aerial view shows the 14-Foot Transonic Tunnel about a year after it reopened. The tunnel's honeycomb appearance, the enlarged motor room at the upper right, and the new air-exchange tower at the upper left are readily apparent. (Photo credit: NASA A-20687)

This 1995 aerial view shows the 14-Foot Transonic Tunnel's appearance during its later years. Comparison with the earlier photograph shows how crowded the area had become by the time this view was recorded. (Photo credit: NASA AC77-0846-011)

NATIONAL FULL-SCALE AERODYNAMICS COMPLEX



This 1944 aerial view shows the recently completed 40- by 80-Foot Full-Scale Tunnel, with a portion of the 16-Foot High-Speed Tunnel at the lower right. The tunnel's external steel framework and asbestos-cement walls are readily evident. The central structure with no external structure houses the test section. The non-rectangular contraction, diffuser, and fan sections were fabricated entirely of steel. (Photo credit: NASA A-13516)

SIGNIFICANCE

The National Full-Scale Aerodynamics Complex (NFAC), originally known as the 40- by 80-Foot Full-Scale Tunnel (40- by 80-Foot FST), and to which the 80- by 120-Foot Full-Scale Tunnel (80- by 120-Foot FST) was added, is the world's largest wind tunnel facility. The 40- by 80-Foot FST was the second NACA tunnel that was large enough to accommodate a full-sized airplane for aerodynamic testing, thus providing a direct comparison and correlation between actual flight and wind tunnel testing. The addition of the 80- by 120-foot tunnel leg allowed larger aircraft to be tested. Though the tunnels' maximum speeds are relatively low, the NFAC continues to host test programs involving aircraft at high angles of attack and advanced rotorcraft. The NFAC also became the

first NASA wind tunnel to be closed and then reopened under the auspices of the Air Force's Arnold Engineering Development Center, which currently manages the tunnel.

DESCRIPTION

The NFAC is a dual-mode wind tunnel that can be configured for closed-circuit or open-circuit operation, depending on the test section size and speed selected. Although originally constructed with only a single, closed circuit having a 40- by 80-foot elliptical test section, the NFAC now has an 80- by 120-foot rectangular cross-section addition that operates as an open-circuit tunnel using the same drive fans and large, movable vanes and louvers to redirect the flow. It can operate in only one of these modes at a time. The original 40- by 80-foot portion is Building Number N-221, and the 80- by 120-foot addition is N-221B.

The 40- by 80-foot closed-circuit tunnel's exterior appearance and basic internal layout remain very close to original. For the entire tunnel except the fan section, contraction, test section, and initial diffuser, corrugated asbestos-cement panels form the side walls of the circuit, and they are topped with pitched roofs of the same material. Modifications to the tunnel have resulted in some of these panels being replaced with corrugated metal panels. The roof is divided into seven major sections to suit the dimensions of the tunnel at each point, and smaller roof sections fill gaps between the major ones. While internal steel trusses support the roof sections, the walls are braced by an external steel structure that bears some resemblance to modern space frames. The more-complex shapes of the contraction, diffuser, and fan sections are steel fabrications, also with external steel supporting structures. All foundations are concrete. Overall, this portion of the tunnel measures 870 feet long by 400 feet wide, and it reaches a maximum height of 160 feet. This defines a footprint of approximately 8 acres, including the open central area.[29]

The test section is enclosed within a structure called the test chamber that looks similar to the other tunnel sections except for having no external structure. It uses a conventional column-and-beam internal steel structure with a concrete ground floor, and it houses a high-bay model-preparation area on its east side as well as five floors on its west side for offices, shops, and test section access. The floor of the test section is at the third-floor level, with the original balance room directly below. An elevator connects all five floors. The 40- by 80-foot elliptical test section, centrally located within the test chamber, measures 80 feet long. After installation of a sound-absorbing liner in 1986, the actual cross-sectional dimensions have been 39 by 79 feet. Its contraction section and diffuser, fabricated of steel, are located largely outside the test chamber structure. An overhead bridge crane with 5- and 35-ton hoists runs on rails approximately 120 feet above the ground floor. It serves to lift test articles, including complete airplanes, into and out of the test section. The top of the test section is composed of two bifolding clam-shell doors that open to provide a 78-foot, 6-inch by 49-foot access to the test section.[30]

The original, mechanical six-component balance originally occupied an enclosed room directly below the test section. Test articles were originally mounted on three

struts that extended up from the balance frame through the test section floor. A control panel in the room originally controlled all tunnel and test article functions, as well as the balance scales' printers. A newer control room adjacent to the test section's west side now controls tunnel and model functions, and a data acquisition system monitors electronic instrumentation.

The tunnel's airflow is provided by a two-level bank of six 40-foot-diameter fans, each with its own variable-speed electric motor housed in a nacelle. When built, each six-bladed fan had a 6,000-horsepower DC motor controlled by a Ward-Leonard system, and all six motors were synchronized to run at the same speed to ensure equal loading among the fans. These fans and motors were later replaced, and the current drive consists of six 15-bladed, variable-pitch fans driven by 22,500-horsepower (18,000-continuous-horsepower) synchronous motors. Air speed is controlled by varying both blade pitch and motor speed. A starting mode uses an induction frequency control system to bring the motors up to 36 revolutions per minute. Varying blade pitch at this speed allows testing with low background noise. More commonly, the motors, once started, are switched to the 60-Hertz utility power, where the six motors operate at 180 revolutions per minute. Adjusting blade pitch controls the test section speed. The original airspeed range was 0–230 mph, but the repowering raised the maximum speed to 345 mph in the 40- by 80-foot test section.[31]

The new drive system was one part of a major rebuilding project during the 1970s and 1980s that added a massive 80- by 120-foot test section in a leg that extends almost 500 feet in a northwesterly direction from the original tunnel. Like the original tunnel, this larger leg uses an external truss framework, but its walls and ceiling are of sheet steel. A metal roof over the test section protects it from the weather and serves to block solar heat. A sound-absorbing liner reduces the actual inside dimensions slightly—to 79 feet high by 118 feet, 4 inches wide. This test section utilizes the same 135,000-horsepower drive system as the closed circuit, but it operates only as an open-circuit tunnel. The original turning vanes in turn 3 were modified with movable vanes to direct the airflow around the turn for the 40- by- 80-foot circuit, or straight ahead to and through movable louvers installed in the tunnel's south wall. These vertical louvers exhaust the air to the atmosphere when open, or form part of the 40- by 80-foot circuit's wall when closed. Additional sets of vanes at turn 2 and at the 80- by 120-foot leg's attachment to the original tunnel also move to configure the desired circuit.[32]

The 80- by 120-foot configuration has a speed range of 0–115 mph. To provide a stable flow of air into the 80- by 120-foot test section, it is fitted with a flared inlet approximately the size of an American football field. Its sides and top include curved cowls to minimize edge disturbances. Guide vanes and flow straighteners mounted in the inlet further stabilize the airflow, and louvers can be closed to protect the entire leg from the weather when not in use.

The floor of the 190-foot-long test section is approximately 20 feet above the ground, and model installation is done through a pair of doors, each 60 feet high by 40 feet wide,

on its northeast side using a 75-ton gantry crane. Its crane rails extend from an outside concrete pad into the test section. Two sections of the floor are removable to allow the crane to convey models—often actual aircraft—fully into the test section and position them onto the model supports.

Both test sections currently utilize three methods to support models: a three-strut support, a semispan mounting, and a sting. These are mounted on turntables in the test section floors that rotate 290 degrees in the 40- by-80-foot section and 344 degrees in the 80- by 120-foot section. The rear of the three struts in each section is vertically adjustable to allow pitch to be varied ±15 degrees in the smaller section and ±35 degrees in the larger section. Semispan models are usually mounted on the turntable with their wings vertical, allowing angle-of-attack changes by rotating the turntable. Other mounting systems can be designed for specific applications. Each turntable is carried on a six-component, floating-frame balance with strain gages connected to a distributed data acquisition system. A wide variety of other instrumentation can be connected to the data acquisition system as needed. Both real-time and posttest data reduction and analysis are available.[33]

A variety of utility services are available in both test sections to support tests using both powered and unpowered models and engines. JP-5 fuel, as well as 28–32 volts of DC electricity and compressed air for starting, permit operation of turbine engines. Commercial utility AC power is available at 120, 208, and 480 volts, as are variable-frequency power supplies able to drive loads as high as 1,900 kilowatts (2,600 horsepower) at 150 Hertz. Smaller drives can operate at up to 400 Hertz. Compressed air at 125 and 3,000 psi can be supplied for instrumentation, tools, and model devices, and hydraulic power sources are also available. Models can be connected to a closed-loop water system in the model-preparation area and in each test section if cooling is needed.[34]

HISTORY

When Smith J. "Smitty" DeFrance moved from the NACA's Langley Laboratory to design and build the new California laboratory in 1940, he brought with him the idea for what became the FST. DeFrance had been the designer and head of Langley's 30- by 60-foot Full-Scale Tunnel (LFST), the world's largest since its opening in 1931, and that tunnel had aptly demonstrated the practicality and value of full-sized testing. But aircraft increased in size and speed during the decade, and DeFrance ultimately envisioned an even larger and faster wind tunnel that could accommodate them. Unfortunately, such a tunnel could not be built at Langley because of its chronic shortage of electrical power, but the new laboratory at Moffett Field, California, had ample power available. Thus, when DeFrance was selected to build a laboratory that was primarily intended for high-speed aeronautical research, his vision for it nevertheless included a very large tunnel.[35]

With construction of the two 7- by 10-foot tunnels and the 16-Foot HST well under way by the end of 1940, DeFrance and his staff, which included John Parsons, H. Julian "Harvey" Allen, and Don Wood, along with assistance from other engineers at Langley,

began to design the 40- by 80-Foot FST. While they drew heavily on experience gained in the LFST, these engineers produced a substantially different design for Ames. Both tunnels were large, atmospheric, closed-circuit tunnels with elliptical test sections, and both utilized externally braced asbestos-cement walls to form most of their circuits, but the major similarities stopped there. The Ames tunnel employed a single-return circuit and six fans driven by six motors that totaled 36,000 horsepower, 4.5 times the power of the LFST. But the most significant difference was the 40- by 80-Foot FST's closed test section. Combined with the single-return circuit and a well-proportioned contraction cone, this design delivered a very uniform, low-turbulence airflow with speed variations within ±5 percent throughout the test section.

The team had essentially completed the 40- by 80-Foot FST's design by fall 1941, but by then there was no money to build it. Ames had used up its original $10 million appropriation, thanks largely to contractors' fears—and experience—over unpredictable and skyrocketing costs as the world devolved into a global war. Ames had no choice but to request another $6 million from Congress. That amount, based on the sole bid to construct the tunnel received from Pittsburgh–Des Moines Steel Company, a leading builder of wind tunnels, was approved in October 1941, and a construction contract was soon signed. Actual construction began in March 1942, and the tunnel was completed in June 1944. John Parsons, DeFrance's construction head, managed the construction project, and DeFrance assigned him to head the newly formed Full-Scale and Flight Research Division even before the tunnel's completion.[36]

Although its completion was fairly late in the war, the 40- by 80-Foot FST nevertheless quickly began to perform valuable wartime work, including tests of the A-26 Invader's nacelles and laminar-flow wings. While most of the aircraft tested were designed for higher speeds than the tunnel's 230-mile-per-hour maximum, these planes also had to fly well at slower speeds, particularly during landings and takeoffs, and the tunnel excelled at such testing. The introduction of swept wings at the war's end placed a new urgency on finding ways to make swept wings and stabilizers perform well at low speeds. The B-47 and F-86, America's first production swept-wing airplanes, spent many hours in the 40- by 80-Foot FST in pursuit of this. When the submerged inlet concept was finally applied to a full-size plane, the FR-1, it was tested in the tunnel before making its first flight.[37]

Virtually all aircraft design concepts and most of the airplanes built since World War II have undergone testing in the 40- by 80-Foot FST. Some of these, like the N9M flying wing prototype, were well ahead of their time in the 1940s and 1950s. Helicopter testing became prominent during the 1960s, and that has continued to be a major task for the tunnel, along with testing of V/STOL aircraft like the V-22 that combine helicopter and airplane design elements.[38]

In 1964, the 40- by 80-Foot FST received an intriguing, non-aeronautical accessory, an apparatus known as the Vertical Height Control Simulator. This two-man pod with vehicle dynamics programmed into an analog computer moved about 100 feet vertically

on rails affixed to the tunnel's south wall structure. The simulator, used for approximately five years, was one of several unique devices used to train Apollo astronauts. It was dismantled during a 1980s rebuilding of the tunnel that required the installation of new louvers in the wall.[39]

By the mid-1970s, NASA realized that the 40-year-old facility needed some upgrading if it was to remain viable, so engineers studied likely future test requirements and came up with an amazing concept. The study indicated that not only could the 40- by 80-foot tunnel be significantly improved with additional power, improved instrumentation, and an acoustic liner, but demand also existed for a low-speed test section about twice that size. More-detailed engineering studies indicated that a new leg could be added to the facility with a test section measuring 80 feet high by 120 feet wide. If total drive power was increased to 135,000 horsepower, that drive could increase the 40- by 80-foot test speed by 50 percent and generate a maximum speed of about 115 mph in an 80- by 120-foot test section. The addition of some movable louvers and vanes would allow the larger test leg to run as an open-circuit tunnel. NASA approved this conceptual design in 1977.[40]

The project proved to be one of the longest in NASA history. Once approved, design, construction, checkout, and calibration took 11 years to complete. The design challenges were numerous, since they involved two interrelated tunnels with different operating parameters. The engineers built a 1/50-scale model of the tunnel that proved to be very useful in working out numerous details throughout the design and construction process. The 40- by 80-foot circuit was completed in 1986, and the larger circuit opened two years later. The dual-tunnel complex was renamed the National Full-Scale Aerodynamics Complex.[41]

The 80- by 120-Foot FST provided an unprecedented capability to test full-scale rotors for helicopters and tilt-rotor V/STOL craft, and it remains the preferred venue for such testing. While the 7- by 10-Foot Wind Tunnel and the 40- by 80-Foot FST are able to do much of the preliminary testing, the larger tunnel allows full-size rotors to operate as much as 50 feet above the floor without significant floor or wall effects. Aerodynamic, aeroelastic, and dynamic test regimes for rotors are supported utilizing several powered devices that resemble helicopter fuselages or tail booms.[42]

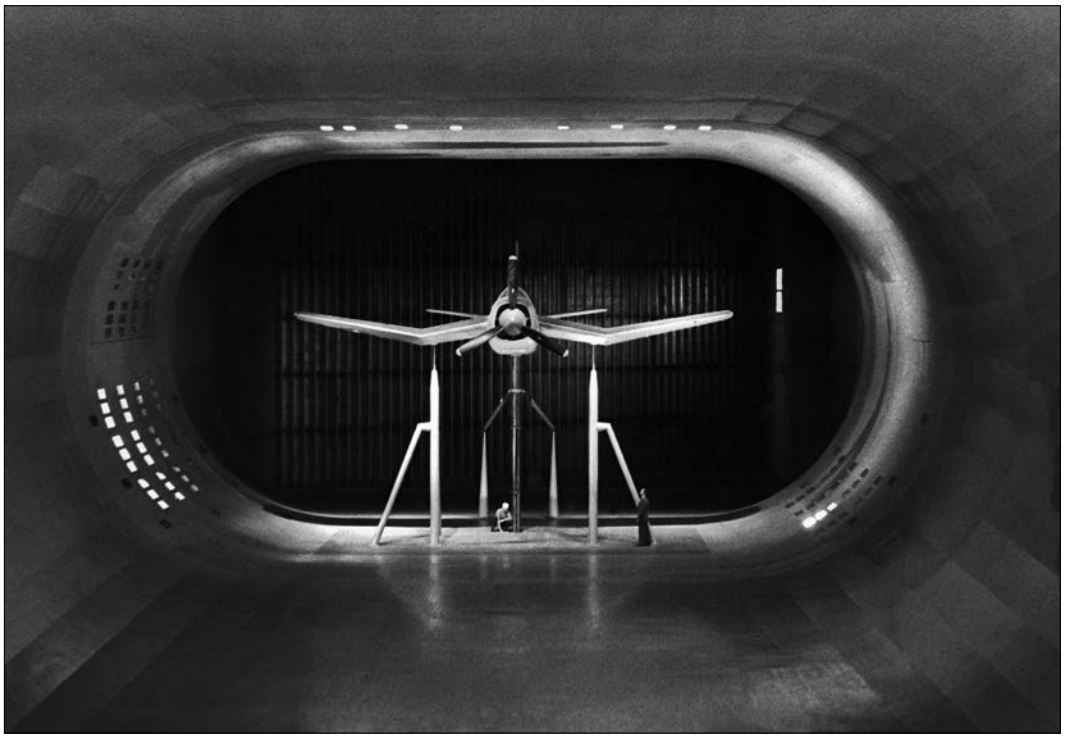
Noting a growing concern with aircraft noise problems, the engineers added acoustic linings in both test sections during the 1990s to support aeroacoustic testing. This has proved valuable for tests involving airplanes, helicopters, and V/STOL craft. While helicopter rotors and jet engines are notably noisy, other sources of noise, such as extended flaps and landing gears, are less obvious, but they have recently come under intense scrutiny as well. Tests in both sections have made major contributions to noise reduction in several areas. In some cases, aerodynamic and aeroacoustic testing can occur simultaneously.[43]

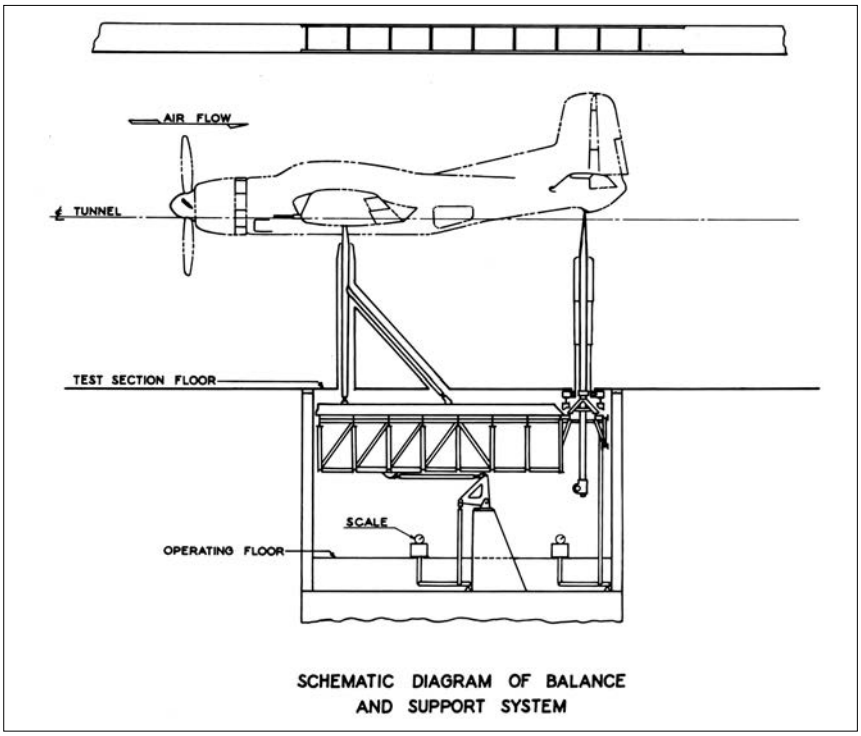
During his 1992–2001 term as NASA Administrator, Daniel S. Goldin instituted a "full cost accounting" program that, among other things, was intended to recover all

wind tunnel operating costs from outside customers. With the numbers of new aircraft designs and manufacturers declining, which caused a corresponding decline in wind tunnel bookings, this program closed or mothballed numerous NASA tunnels, including the NFAC. At one point in 2001, only one outside test program inquiry had been made regarding time in the NFAC, so the rules demanded that the potential client be quoted the NFAC's total cost for the entire year. The client made other arrangements to test offshore, and no other inquiries from outside clients followed. Although there was still some limited NASA and Army research in the NFAC, NASA decided to close it in May 2003 and did so in October, following a Mars Exploration Rover parachute test. Some of the NFAC staff was relocated within Ames, but many were furloughed.[44]

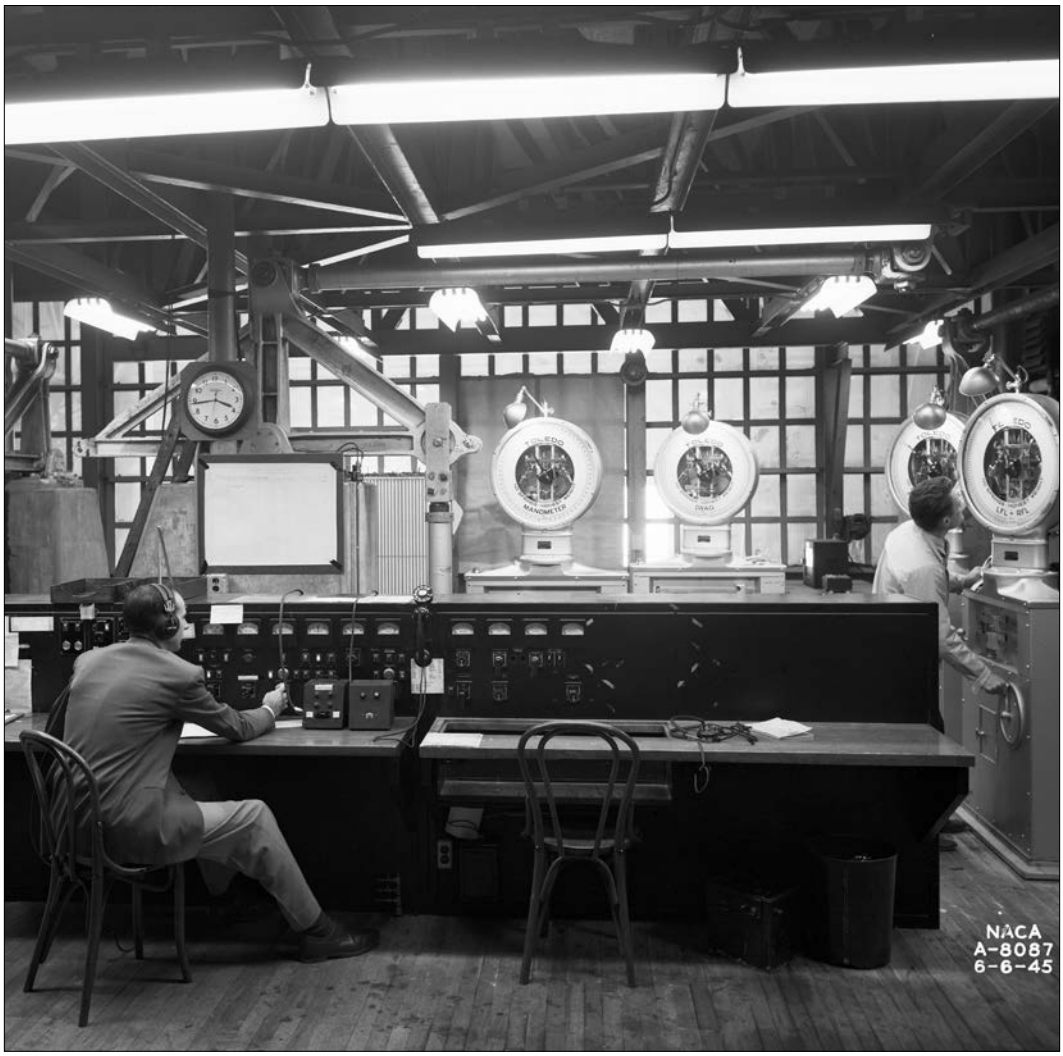
Immediate protests from the Army and the American Helicopter Society insisted that the NFAC was essential to rotorcraft development work regardless of its utilization time or cost recovery. Rotorcraft projects might not be numerous, but no other facility could host the essential testing. The protests reached Secretary of Defense Donald Rumsfeld, who understood the problem but did not want to establish a new bureaucracy within the Army, even though the Army was the primary customer. Instead, Rumsfeld turned to the Air Force's Arnold Engineering Development Center (AEDC) in Tullahoma, Tennessee, which already managed an ex-Navy tunnel in White Oak, Maryland, and determined that the NFAC could reopen under AEDC's management. In 2006, the Air Force signed a 25-year lease of the NFAC with NASA.[45]

Restarting the NFAC took some time, both to get the facility back in shape and to rebuild an operating staff. Several former leaders returned, but much of the staff had to be hired and trained. Full operation of the NFAC resumed in 2008, and the complex remains in service. While the Army remains the NFAC's largest customer, the facility is available for other programs. NASA retains full ownership of the NFAC, but, interestingly, it must now pay the Air Force to use the facility.[46]

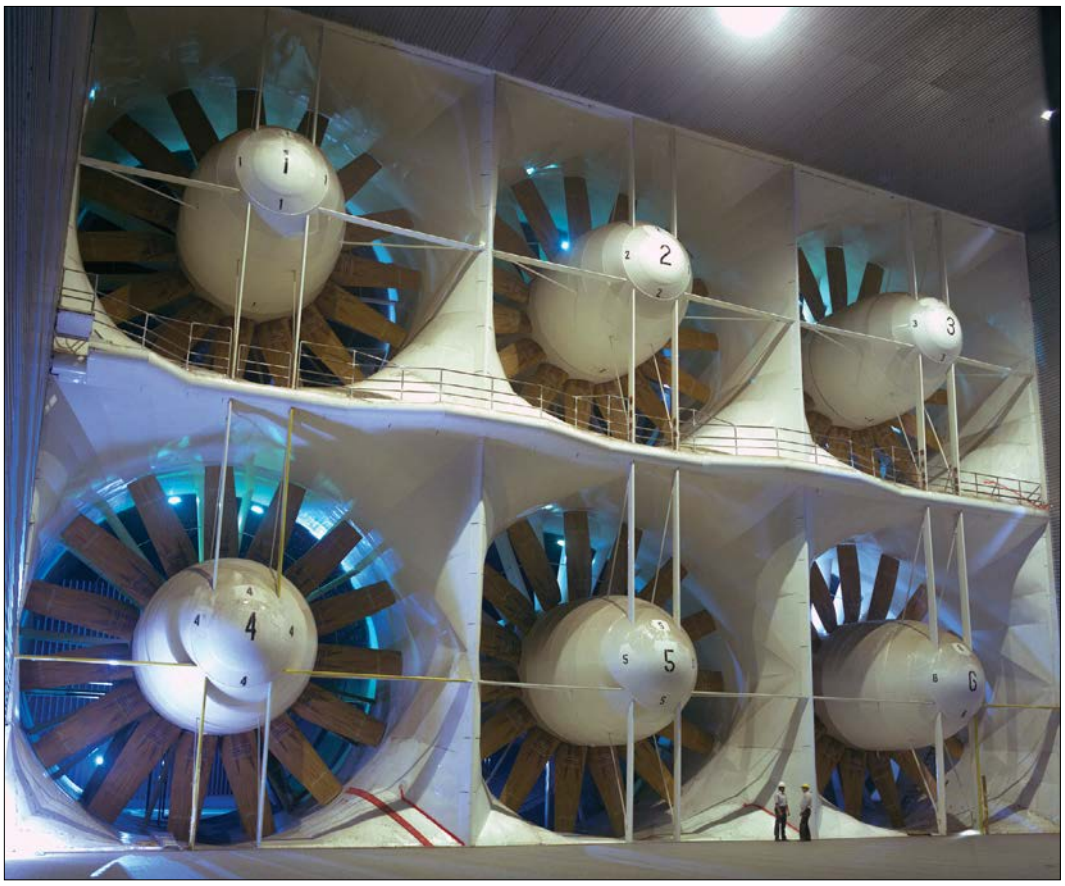




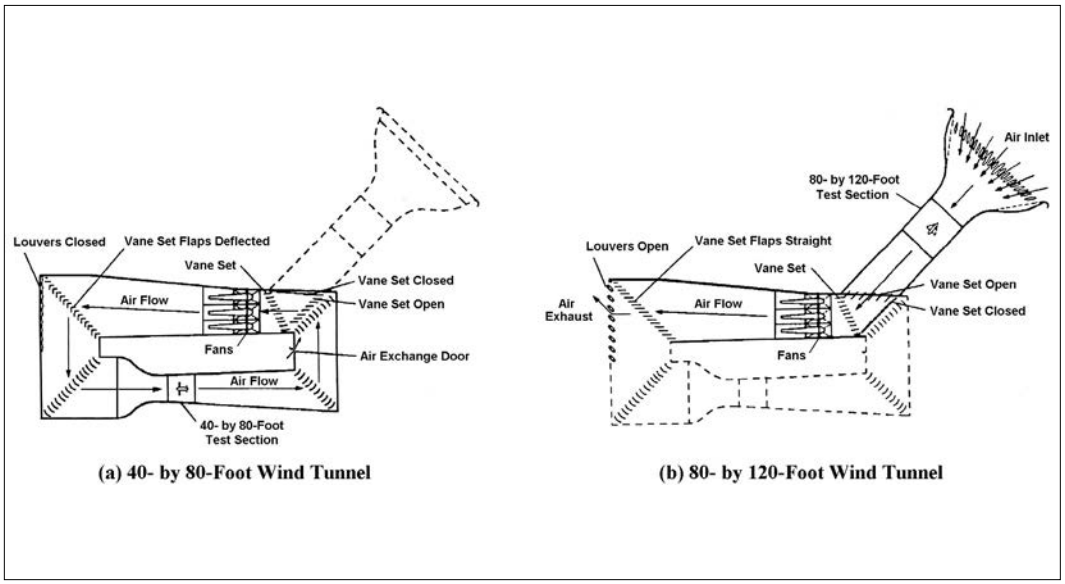
An XSB2D-1 mounted for testing in the 40- by 80-foot test section in 1944 (top) and a side view drawing of the test section and balance system (bottom) give a sense of its size and layout. Note the man kneeling under the airplane. An overhead crane is used to transfer test specimens between the preparation (working) area and test section through clamshell doors in the ceiling. (Photo and Image credit: NASA AAL-5985 and NASA A-7614)



The 40- by 80-Foot Full-Scale Tunnel's original balance and control room was located directly below the test section. The scale system shown here in 1945 was the typical instrument employed before the advent of electric strain gages. (Photo credit: NASA A-8087)



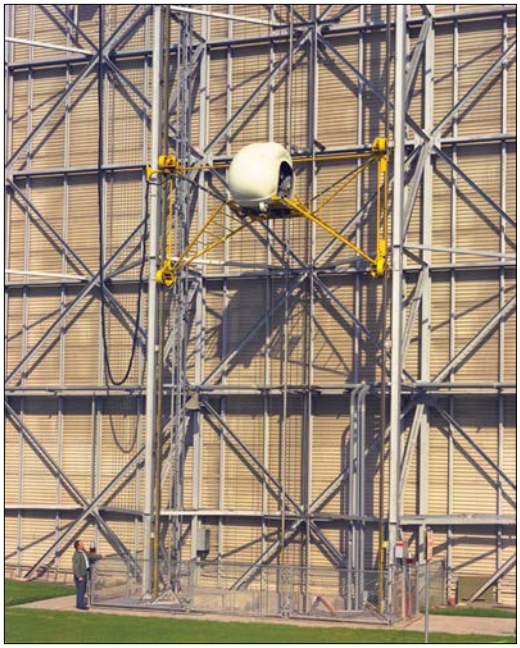
This bank of six fans drives the National Full-Scale Aerodynamics Complex in both modes. Each 40-foot-diameter fan, originally driven by a 6,000-horsepower motor, is now turned by a motor producing 22,500 horsepower. For a sense of scale, note the two men standing on the floor in this 1986 photograph. (Photo credit: NASA AC86-8016)



These two drawings show the two operational modes of the National Full-Scale Aerodynamics Complex after installation of the 80- by 120-foot test section in 1988. Unused portions of the facility for each mode are shown dashed for clarity. (Image credit: NASA TM-102827, Fig. 6)

These two early 1990s photographs show an F/A-18 being installed in the National Full-Scale Aerodynamics Complex's 80- by 120-foot test section. Note how the gantry crane can move completely inside through the large doors. (Photo credits: NASA AC93-0150-114 and NASA AC91-0255-075)

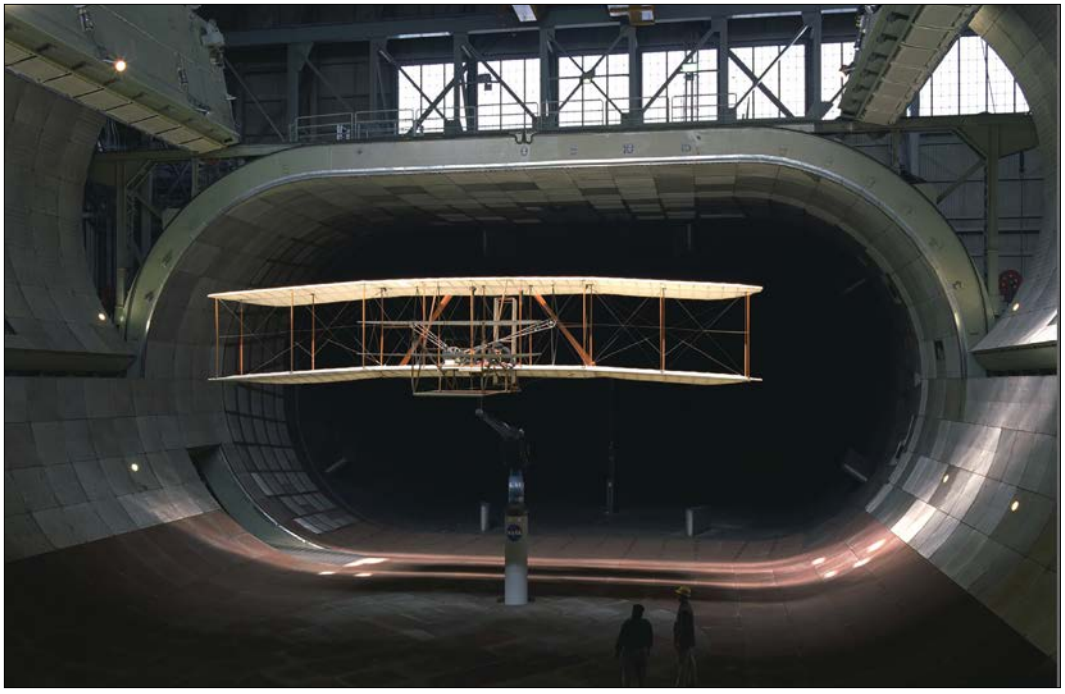
This 1982 aerial view shows the National Full-Scale Aerodynamics Complex, with its 80- by 120-foot test section and inlet at the lower right. The extent to which the NFAC dwarfs Ames's other tunnels is readily apparent in this view. (Photo credit: NASA AC82-0551-55)



This 1969 photograph shows the Vertical Height Control Simulator, mounted on the south wall of the 40- by 80-Foot FST, which helped train Apollo astronauts in the 1960s. (Photo credit: NASA AC-42137)

A ⅓-scale model of the Space Shuttle orbiter set up for landing approach tests in the 40- by 80-foot test section in 1975. (Photo credit: NASA AC75-1161-3)

A 1992 test of the McDonnell Douglas Advanced Rotor in the reopened National Full-Scale Aerodynamics Complex involved this advanced helicopter rotor design in the 40- by 80-foot test section. Note the man on the lift truck for scale. (Photo credit: NASA AC92-0078-1)



This centennial replica of the 1903 Wright Flyer was one of the more unusual planes tested in the National Full-Scale Aerodynamics Complex. This 1999 view shows the 40- by 80-foot test section's clamshell doors open. (Photo credit: NASA AC99-0030-5)

1- BY 3.5-FOOT HIGH-SPEED TUNNEL

The 1- by 3.5-Foot High-Speed Tunnel, located in the 16-Foot High-Speed Tunnel's central courtyard, was dwarfed by its host. Note the simple construction in this 1944 photograph, the hoist frame over the circular fan section (with a man kneeling on top), and the air-exchange tower to the right of the fan section. (Photo credit: NASA A-6244)

SIGNIFICANCE

The 1- by 3.5-Foot High-Speed Tunnel (1- by 3.5-Foot HST) was a relatively small high-speed tunnel built quickly to provide an inexpensive venue for the two-dimensional testing of airfoils at near-sonic speeds. It was never intended to be a permanent research facility, but data from tests in the tunnel contributed much to the basic understanding of aerodynamics near Mach 1.

DESCRIPTION

The 1- by 3.5-Foot HST was a closed-circuit, single-return atmospheric wind tunnel located in the central courtyard of the 16-Foot HST (Building N-218). It was a basic design that incorporated no novel concepts. Few records exist concerning this tunnel, so much of its description was gleaned from one plan sketch and a few surviving photographs.[47]

The 1- by 3.5-Foot HST had a rectangular cross section, except for a circular section at its fans and the transitions into and out of the fan section. It was constructed of steel plate supported by an external structure fabricated from wide-flange members and

limited amounts of square steel tube. The entire structural frame, as well as the shell, was arc-welded. The appearance strongly suggests that the primary frame, which stands away from the tunnel walls on visible rectangular sections, was fabricated separately from the walls, some of which had additional structural shapes applied for stiffness. The fan and transition sections had structures integral to their walls to follow and stiffen the complex contours. The fan section had four circumferential rings and a reinforced wall to support an internal nacelle via streamlined struts.

The nacelle enclosed two 1,000-horsepower, variable-speed electric motors, each of which turned a 6-foot, 6-inch-diameter fan. Each fan was on an independent shaft to a single motor. The existing 16-Foot HST used counter-rotating fans to minimize swirl, but available documents give no indication whether the designers incorporated this feature in the 1- by 3.5-Foot HST. The single control knob adjacent to the dual ammeters in one photograph suggests that the two motors could not be independently controlled but always ran at the same speed. The general design of the tunnel and test reports indicate that it could achieve a maximum of approximately Mach 0.85 with a model in place. A steel structure straddled the fan section to support two I-beam rails for a monorail hoist that was used to install and maintain the fans and motors.[48]

The tunnel's settling chamber measured 7 feet wide by 8 feet high, which the contraction reduced to 1 foot wide by 3 feet, 6 inches high at the test section's entrance. This gave the tunnel a 16:1 contraction ratio. Although the plan sketch shows no anti-turbulence screens, this contraction ratio delivered a smooth airflow for such a relatively unsophisticated tunnel.[49]

The two-dimensional test section was located at one end of a 20- by 25-foot test enclosure built of wood. The interior was spartan, and the tunnel's controls were contained in a cabinet supported by a shelf along one wall. Portable multitube manometer racks were employed for pressure measurements, which were the primary parameters measured in the airfoil tests. Small models of complete airplanes could be tested using custom-built sting mounts.

A vent tower between the fans and Corner 3 exchanged a fraction of the tunnel's air for atmospheric air to remove the heat generated by the fans and motors. Hinged flaps on the tunnel's walls allowed operators to adjust the amount of air exchanged. The tower, which rose about 4 feet over the tunnel, was built of wood and covered with a corrugated metal roof.

HISTORY

As airplanes rapidly increased in size and speed during World War II, the demand for high-speed testing at Ames increased accordingly. The laboratory's 16-Foot HST had entered service late in 1941, but it quickly became fully booked and limited to the highest-priority test programs during the conflict. Badly needing a venue for basic high-speed airfoil research, engineers at Ames had to think creatively to come up with

a solution. Fortunately, such an airfoil tunnel did not need to be large, and previous work at Langley had proven that two-dimensional test sections were well suited to airfoil testing.[50]

Taking a conservative course to minimize the cost, the Ames engineers designed the 1- by 3.5-Foot HST to be a two-dimensional, high-speed tunnel specifically tailored for airfoil testing. Designing the 1- by 3.5-Foot HST was not particularly difficult, since it would not have to introduce any new technology. Finding the funds to build it was another matter. No records regarding its funding have been found, suggesting that it was one of the NACA's "bootleg" projects that were actually funded through the careful management of other, formally funded projects. This is supported by the general mood and conditions of the time as well. With the ongoing expense of the war, Congress was interested only in essentials that would have direct and rapid effects on its conduct. Thus, there seems to have been no alternative to the engineers, researchers, and managers at Ames creatively funding what they needed—in other words, a bootleg project.

The 1- by 3.5-Foot HST was constructed using common materials available at the laboratory: steel structural sections and plate, wood, and corrugated metal. The motors and instrumentation likely came from items in storage, and the machining and fabrication needed were well within onsite capabilities. This gave the 1- by 3.5-Foot HST some unique details, including its welded frame. While welding was commonly being used to join plates into ships and pressure vessels, it was not yet widely used for joining structural steel members, especially outside of a fabrication shop. Rivets and bolts remained the preferred method for field assembly in the 1940s. For the shop people at Ames, though, the site inside the 16-Foot HST's courtyard was essentially like their shop floor, making onsite welded construction quicker and cheaper than machining individual pieces in the shop for riveted field assembly.

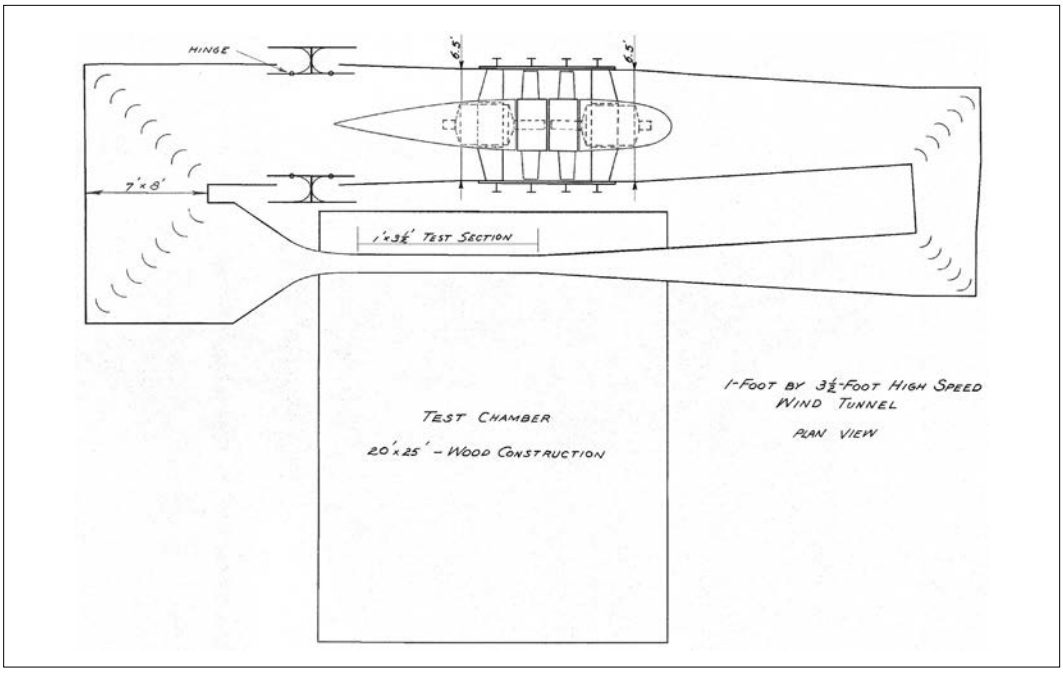
The 1- by 3.5-Foot HST entered service in January 1944, though there was no official opening ceremony marking the event. The airfoil tested typically spanned the 1-foot width of the test section with their ends penetrating hatches in the walls to allow easy connection to static pressure taps machined into the model. Soft seals prevented leakage into the test section to ensure true two-dimensional flow, and the models could be rotated to different angles of attack. Lift, drag, and pitching moments were computed from pressure measurements taken at the floor, at the ceiling, and in the model's wake. These pressure measurements were photographically recorded on multitube manometers.[51]

Small models also were tested in the 1- by 3.5-Foot HST, including the YP-80A prototype for America's first operational jet fighter. The 1/78-scale model, which had a 6-inch wingspan, was mounted on a sting, and it contained an internal strain gage to measure pitch. The remaining lift and drag strain gages were part of the sting. No dynamic pitch control was available, so separate stings were constructed for each angle of attack desired.[52]

Coupled with data from other tunnels, tests in the 1- by 3.5-Foot HST contributed to a basic understanding of high subsonic and low transonic aerodynamics, including how the role of airfoil camber changed as speed increased and the nature of changes in local airflows caused by shock formation. This information led to the construction of larger models using the best airfoils in other tunnels, including the new slotted-wall transonic tunnels. Having served its intended role, the 1- by 3.5-Foot HST was closed in 1951, but it was modified and reopened in 1959 for a test program that investigated pressure distributions over some simple airfoils to evaluate the effects of perforated-wall interference on transonic tests. Looking for an inexpensive test venue, Ames engineers modified the 1- by 3.5-Foot HST's test section with a perforated floor and ceiling. The modification involved new floor and ceiling panels that had been drilled with a precise pattern on 0.266-inch-diameter holes. Each of these panels had a matching panel that could slide one-half inch along it to partially obstruct the holes. Welded, these perforated panels in the test section 3.5 inches inside the original floor and ceiling created two plenums. Additional entry and exit panels streamlined the surface and allowed a small adjustment of the plenum reentrainment gap, called the "effuser," at the inlet to the diffuser. Though they could not be moved during a run, the sliding plates could be preset to vary the total wall porosity within a range of 2 to 10 percent, giving the researchers a way to determine how different porosities affected wall interference.[53]

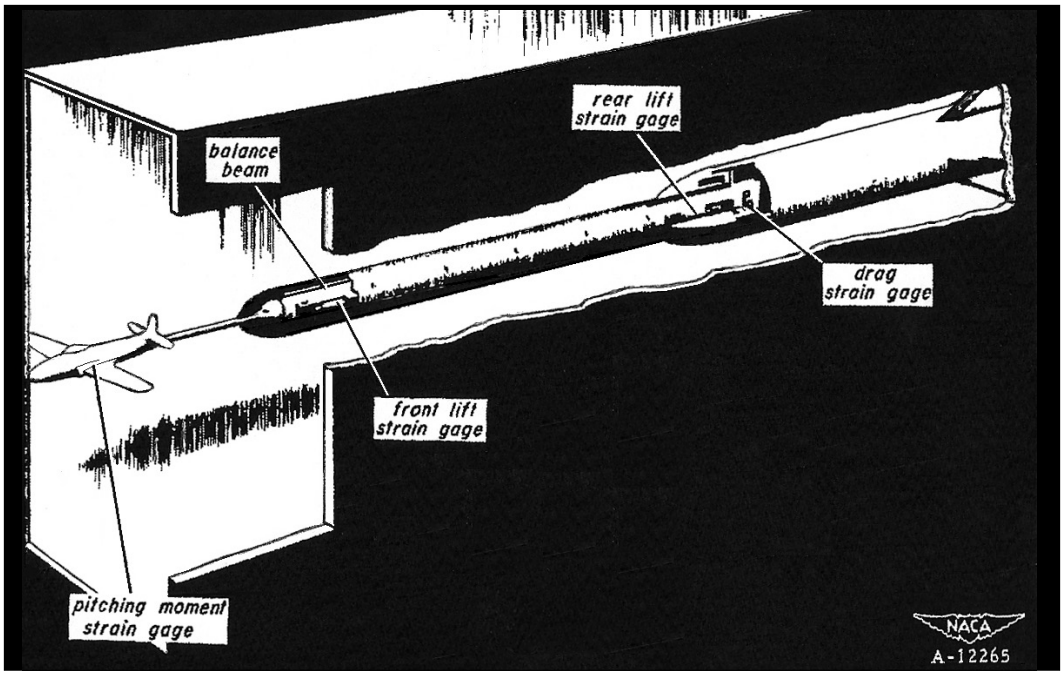
With the perforated floor and ceiling, the 1- by 3.5-Foot HST—which retained that name in spite of its dimensional change and shift from the "high-speed" to "transonic" speed range—produced stable flow between Mach 0.7 and 1.1. The tests run in the modified tunnel partially validated recently developed theory regarding perforated-wall interference, but agreement very close to Mach 1 was poor.

The precise date of the last closing and subsequent demolition of the 1- by 3.5-Foot HST seems to have been lost, but such records were often scarce for bootleg facilities. Available records indicate that it was likely demolished between 1962 and 1965. No portion of the tunnel is known to survive.[54]

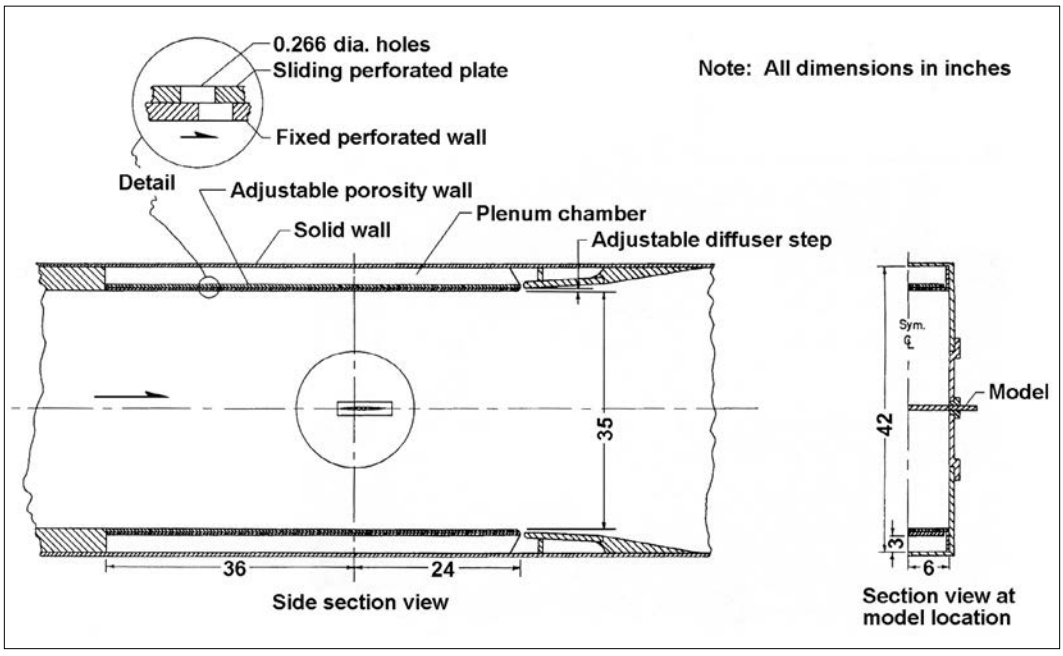


This drawing shows the basic arrangement of the 1- by 3.5-Foot High-Speed Tunnel. The flow was counterclockwise. (Image credit: NASA ARC-1x3.5 HST-2)

This 1944 view of the 1- by 3.5-Foot High-Speed Tunnel's test chamber shows its test section (L background), controls (R), and portable multitube manometer panels with a camera stand in the foreground. (Photo credit: NASA A-6245)



This drawing shows the sting used for testing airplane models, including how strain gages had to be located to measure the aerodynamic forces on the model. With models this small (6-inch wingspan), it was not practical to measure yaw and roll moments. (Image credit: NASA A-12265)



In 1959, the 1- by 3.5-Foot High-Speed Tunnel's test section was modified with the addition of perforated floor and ceiling panels. The novel design used sliding plates against fixed ones to achieve adjustable porosity. The modification reduced the test section's height by 7 inches and allowed stable transonic operation between Mach 0.7 and 1.1. (Image credit: NASA ARC-1x3-5HST-6)

1- BY 3-FOOT SUPERSONIC TUNNEL NUMBER 1 PROPULSION SIMULATOR CALIBRATION LABORATORY

This view of the 1- by 3-Foot Supersonic Tunnel Number 1 in 1945 shows one of the fixed nozzles installed. Part of the schlieren apparatus, a manometer cabinet, the control console, and a portion of the compressor and duct system are also visible. Airflow is left to right in this view. (Photo credit: NASA A-1x3SST-17)

SIGNIFICANCE

The 1- by 3-Foot Supersonic Tunnel Number 1 (1- by 3-Foot ST No.1) was the second supersonic wind tunnel to operate at Ames and likely the second NACA tunnel to successfully use a variable-contour nozzle that allowed changes in Mach number. It also was the first NACA tunnel to employ multiple compressors that could be connected in various ways to suit the desired test conditions. After its aerodynamic duties had been assumed by other tunnels, the 1- by 3-Foot ST No. 1 was converted into the Propulsion Simulator Calibration Laboratory (PSCL), a facility for the calibration of air-powered aircraft models prior to tests in other tunnels.

DESCRIPTION

The 1- by 3-Foot ST No.1 was a closed-circuit, supersonic tunnel that used a variable wall or a fixed nozzle and an array of compressors to generate test conditions of Mach 1.2 to 2.2 at pressures of up to 4 atmospheres (59 psi). The tunnel, which occupied a high-bay room on the south side of Building N-207, consisted of a cylindrical settling chamber;

the nozzle assembly; a test section with circular, optically clear windows suitable for schlieren photography; an array of five air compressors; and associated ducting. A console next to the diffuser contained the tunnel's operating controls, and a large, multitube manometer panel near the test section provided pressure measurements.

The 1- by 3-Foot ST No. 1 shared a wing of its building with the similarly sized blowdown 1- by 3-Foot ST No. 2, and the two tunnels used the same set of interchangeable nozzles. The primary nozzle had flexible walls that could be reshaped to obtain a range of supersonic Mach numbers. Eight electric motors, four per side acting through reduction gearboxes, turned jackscrews that altered the shape of flexible top and bottom plates to recontour the nozzle for the desired Mach number. The sidewalls were fixed in place. Two fixed nozzles designed for specific Mach numbers were also available. The Baldwin Locomotive Works' Southwark Division fabricated all of these nozzles. In the 1- by 3-Foot ST No. 1, which could run continuously, the variable-speed nozzle could be adjusted during test runs if desired.[55]

The 1.0- by 2.8-foot test section was equipped with an optically clear circular window on each side to permit schlieren photography. These windows were mounted in doors that provided access to the model. Most models were sting-mounted and utilized internal strain gages to sense force and moment data, and the large manometer panel supported pressure measurements at multiple points. A camera photographed the panel during test runs for later data takeoff and analysis.

Four air compressors, each a Carrier Model 18P driven by a 2,500-horsepower synchronous electric motor, were connected in parallel between the diffuser exit and the supply duct to the nozzle. Each compressor had a bypass valve so it could be isolated from the circuit, depending on the power needed for any particular test. A water-cooled intercooler after the compressors removed the heat added by the compressors. Its cooling water circulated through a cooling tower outside the southeast corner of the building.

Compressor 5, driven by 7,000- and 1,000-horsepower electric motors, an aftercooler, and a bypass duct around the test section, was added about 1954, along with forced-draft blowers to cool the motors for Compressors 1 through 4, thereby increasing their rating to 3,000 horsepower. With the 9,000-horsepower short-time rating of the fifth compressor's motors, the tunnel's total available power increased from 10,000 to 21,000 horsepower. The test section bypass allowed easier starting and reduced shock loads on models.

HISTORY

The NACA's plans for the Ames Aeronautical Laboratory had included facilities for supersonic research from its inception, but wartime priorities initially focused its efforts away from that regime. Nevertheless, as the war moved toward its conclusion, military planners began to think about postwar needs. For the Air Force, which would become its own service branch in 1947, and the Navy, the future would undoubtedly include supersonic flight. Planners at Ames realized the same thing, and, as money became

available, they started to build the facilities they would need to investigate the supersonic regime. The first would be a 1- by 3-foot (actually 1.0- by 2.8-foot) tunnel to gain some experience before following that with a larger supersonic tunnel. Led by H. Julian "Harvey" Allen, head of the Theoretical Aerodynamics Section, Ames engineers realized they might be able to build not one, but two, of these tunnels by using compressed air from the 12-Foot Pressure Wind Tunnel to power one of them (just as air from the VDT had been used in a pair of high-speed blowdown tunnels years earlier at Langley).

The 1- by 3-Foot ST No. 1, the one Headquarters would know about, would be electrically powered and provide continuous flow. An appropriation of $1,250,000 was approved for it through the proper channels, but the blowdown 1- by 3-Foot No. 2, erected alongside the first, was a classic NACA "bootleg" affair. It nevertheless proved to be quite valuable because Allen and his team got this simpler tunnel into service quickly and gained some sorely needed experience that helped debug the more-complex 1- by 3-Foot ST No. 1. Both of these tunnels were completed within the budget for the 1- by 3-Foot ST No. 1 by August 1945, but it took several more months to get them, especially the 1- by 3-Foot ST No. 1, fully into service.[56]

A crucial part of this experience involved the flexible-wall nozzles used in both tunnels to vary the air speed. While Langley's strike-delayed 4- by 4-Foot Supersonic Tunnel would incorporate flexible walls, no tunnel using them had yet run, so Allen's team became the first to explore this new territory. Allen chose to fix the sidewalls in place and make the top and bottom walls flexible, an arrangement rarely used elsewhere. (Most flexible-wall tunnels had their sidewalls movable, as this gave better maintenance access to the complex system of jacks or cams needed to move the walls.) So uncertain were Allen's conservative engineers of how well the flexible walls would perform that they had the fabricator, the Baldwin Locomotive Works' Southwark Division, make two fixed nozzles as well, each designed for a different speed.[57] As it turned out, they were needed because the flexible walls proved to be troublesome, especially when the tunnels were under pressure. Numerous adjustments were needed to consistently achieve the precise contours required throughout the speed range, and the elimination of leaks at the seals between the fixed and movable walls proved to be a surprisingly vexing problem. But having three nozzles provided a bonus as well. Since all three were interchangeable in both tunnels, the "extra" nozzles allowed test or setup operations to proceed simultaneously.[58]

Allen's insistence on pressurizing the 1- by 3-Foot ST No. 1 was a matter of some controversy. No less an authority than Theodore von Kármán at the California Institute of Technology believed that Reynolds number effects would vanish at supersonic speeds, but Allen persisted. Fortunately, he succeeded, and the tunnels were built to run at pressures of up to 4 atmospheres (59 psia). Once the tunnel began operation, it immediately became clear that the Reynolds number retained its significance regardless of speed.[59]

Allen's team of engineers chose an unusual drive arrangement for the 1- by 3-Foot ST No. 1. Axial-flow compressors, the multistage, turbine like devices now used in

most jet engines and supersonic wind tunnels, were still in their infancy and not fully understood in the mid-1940s. They held promise for use in high-speed wind tunnels, and Langley had a small one in service plus a larger one designed for the strike-dormant 4- by 4-Foot ST, but Allen did not want developmental problems with two new—at least to him—technologies, especially in a facility that needed to be built on a modest budget and operating quickly. So, instead of using a single, axial-flow, variable-speed compressor, his team employed a set of four essentially off-the-shelf centrifugal compressors installed in parallel between the diffuser and nozzle-supply ducts. Valves and independent motor controls let operators use as many as were needed to obtain the desired Mach number. The four electric motors driving these compressors could deliver 10,000 total horsepower, but many tests did not require the operation of all four compressors. Depending on speed and pressure, tests generally needed between 25 and 88 percent of this capacity.

Once the operation and adjustments of the variable-speed nozzle were understood and its leakage problems mitigated to an acceptable level, the 1- by 3-Foot ST No. 1 began to host some serious research into the nature of supersonic flight. Much of the earliest work examined the basic performance characteristics of wings above Mach 1 to understand the lift-to-drag ratios of various planforms, as well as how their centers of pressure and pitching moments changed. Soon, researchers began making more-detailed studies of other parameters, such as pressure distribution, and they began to use these data to refine their theoretical models. For at least the next decade, faster airplanes and an improved understanding of the underlying theory developed hand in hand, supported by many hours of wind tunnel testing.[60]

Throughout the 1950s, research into virtually every aspect of supersonic flight continued at a brisk pace at Ames, the NACA's other laboratories, manufacturers' facilities, and universities. Cold War fears and the military's demands for increasingly faster airplanes furnished the support for these endeavors. Between 1949 and 1952, researchers at the 1- by 3-Foot ST No. 1 sought to take advantage of this and submitted a number of proposals to upgrade their tunnel, but none came to fruition until Congress approved the money as part of the NACA's 1954 budget. The researchers hoped to double the tunnel's Mach number through the addition of a fifth compressor and other modifications to roughly double the tunnel's total power. There is, however, no evidence that the modifications improved its performance as much as expected.[61]

By the end of the 1950s, guided missiles and the so-called "space race" started to shift research priorities away from high-speed aeronautics as the NACA became the core of NASA, an organization charged by Congress with very different goals and priorities. The supersonic work that remained needed faster, more-sophisticated tunnels than the 1- by 3-Foot ST No. 1, and it fell into disuse. But a novel idea ultimately gave the tunnel a second life.

Researchers at Ames had been involved with a wide variety of concepts for V/STOL airplanes since the early 1950s. Though the results generally had been disappointing,

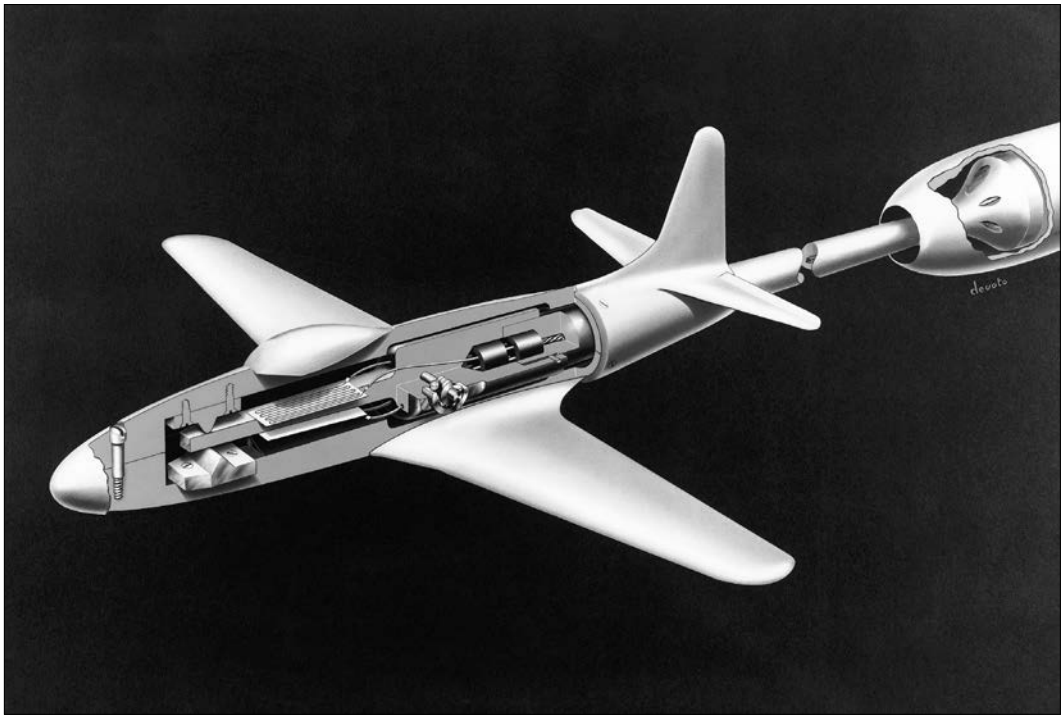
particularly when trying to obtain V/STOL capability in a high-performance plane like a fighter, the idea would not die, and Ames continued to explore it, along with ways to minimize the research costs. One way was to do as much testing as possible in the smaller tunnels and, thus, keep both operating and model costs low. By their very nature, V/STOL models had to be powered, and the airflows around the models were a mixture of the air stream and the propulsion exhaust(s). This led to the development of a small, air-powered turbojet engine simulator known as the compact multimission aircraft propulsion simulator (CMAPS) in about 1977.[62] It proved to be ideal for simulating engines in V/STOL models, but precision calibration of the entire propulsion system, including inlets, bypass passages, and exhausts, was essential and very time-consuming. To reduce the calibration time spent in tunnels, engineers developed a plan to calibrate such air-powered models in a separate facility and then carefully transfer the calibrated model to the desired tunnel for testing. After determining the criteria for such a calibration facility, they decided that the obsolete 1- by 3-Foot ST No. 1 could be rebuilt into one. The key components were the interconnected compressors. They had the range of volumetric capacities needed to maintain any required static pressure in a sealed tank by evacuating the compressed air fed in to operate the engine simulator.

The calibration tank replaced the 1- by 3-Foot ST No.1's nozzle and test section. A cylindrical steel tank with elliptical ends, it measured 12 feet in diameter by 25 feet long. One end was connected to the tunnel's diffuser duct leading to the compressor array, and the other end opened on large hinges to provide unobstructed access to the tank. Six hydraulic clamps operated by a manual pump secured it closed. An exhaust through the building's roof was added to the compressor duct system for the release of extracted air. A new control room constructed next to the tank housed the PSCL controls, CMAPS controls, and a data acquisition system compatible with Ames's standard wind tunnel data acquisition system. The tank had a circular window in its side that allowed operators to see the model from the control room and an internal, overhead monorail hoist for handling models.

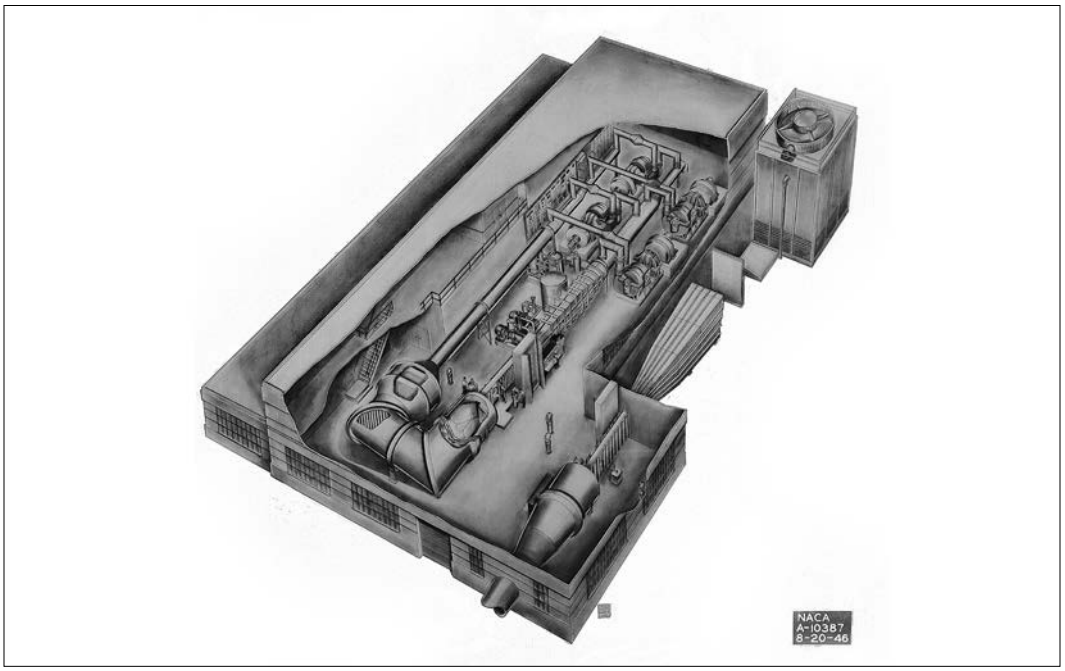
To ensure the most accurate calibrations possible, the engineers also designed a balance frame that rested on hydrostatic bearings to virtually eliminate horizontal friction. This frame included a sting mount with load cells to measure model forces and additional load cells to measure forces between the frame and a fixed reference. All wires and airlines to the model were made as flexible as possible, and they were attached to the balance frame. After calibration, the balance frame, with the model and connections in place, could be removed and installed in the test wind tunnel without any changes to the setup. Carefully done, the model needed only brief checks to verify the calibration before test runs.

Renamed the PSCL, the facility went into service about 1982. Since it was a model preparation device rather than a research facility, its operation generated none of the technical notes, memoranda, and reports that NASA customarily publishes to distribute test program information. Except for a few papers published by the American Institute

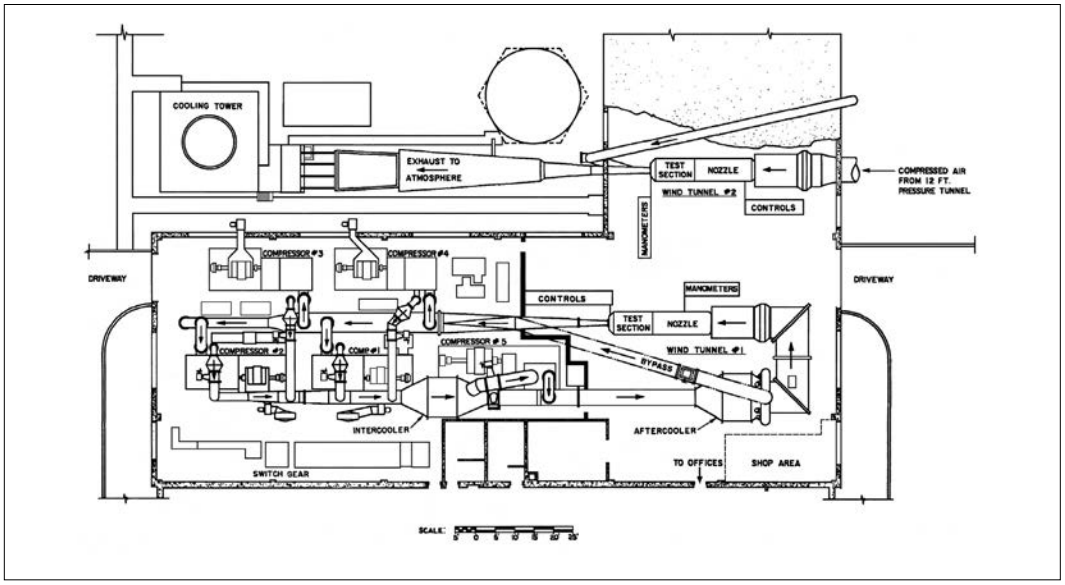
of Aeronautics and Astronautics that describe the PSCL, little has been recorded about its operation and longevity. It appears that Ames closed the PSCL during the 1990s, a period that witnessed a decline in aeronautical research and the closure of several other facilities at the center. The PSCL's control room was cleared of equipment, and it became the location of Ames's historical archives. Except for the control room equipment, the PSCL remained essentially intact but inoperable for many years. The PSCL was eventually demolished, and its associated compressors were removed.[63]



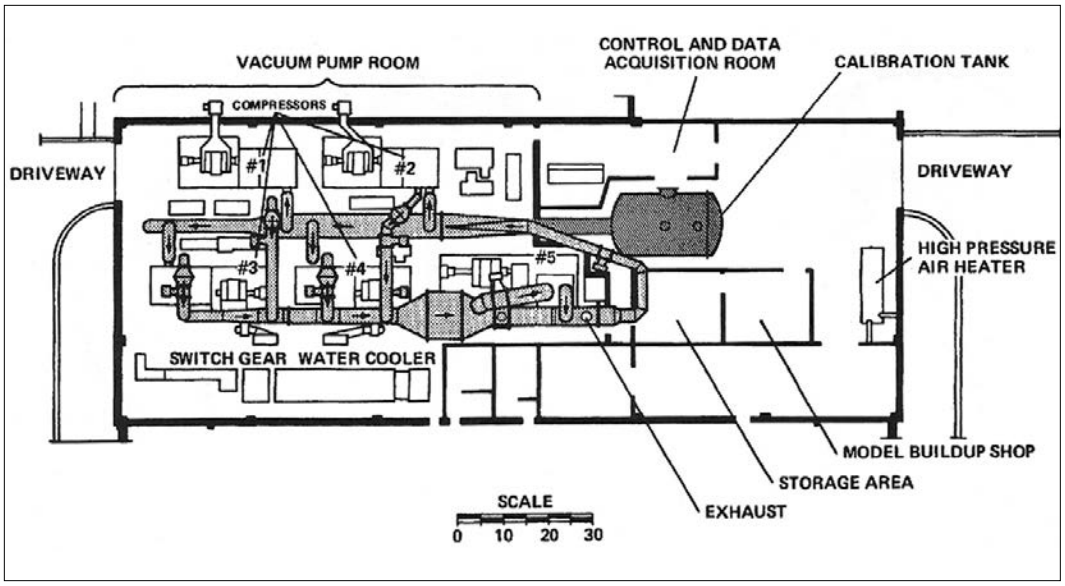
This 1947 cutaway drawing shows a sting mount penetrating a model P-80 with strain gages inside the fuselage to measure aerodynamic forces. The two 1- by 3-foot supersonic tunnels at Ames were among the first built without external balances, thus relying solely on strain gages for force and moment measurements. (Image credit: NASA A-11807)



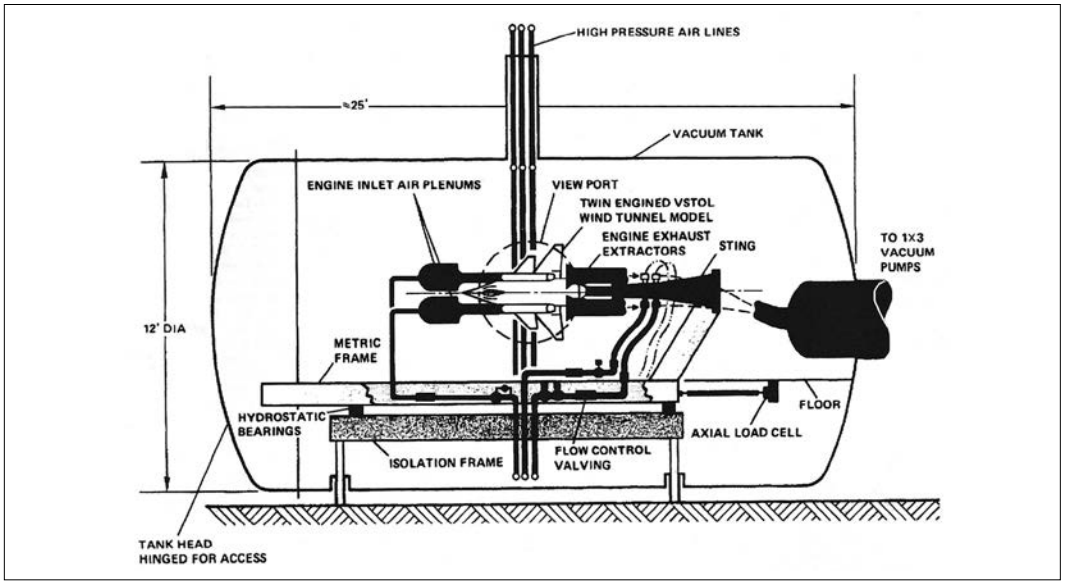
Both the 1- by 3-Foot ST No. 1 (L) and the 1- by 3-Foot ST No. 2 (R) are visible in this cutaway drawing. Note that only the four original compressors of the 1- by 3-Foot ST No. 1 are shown. (Image credit: NASA A-10387)



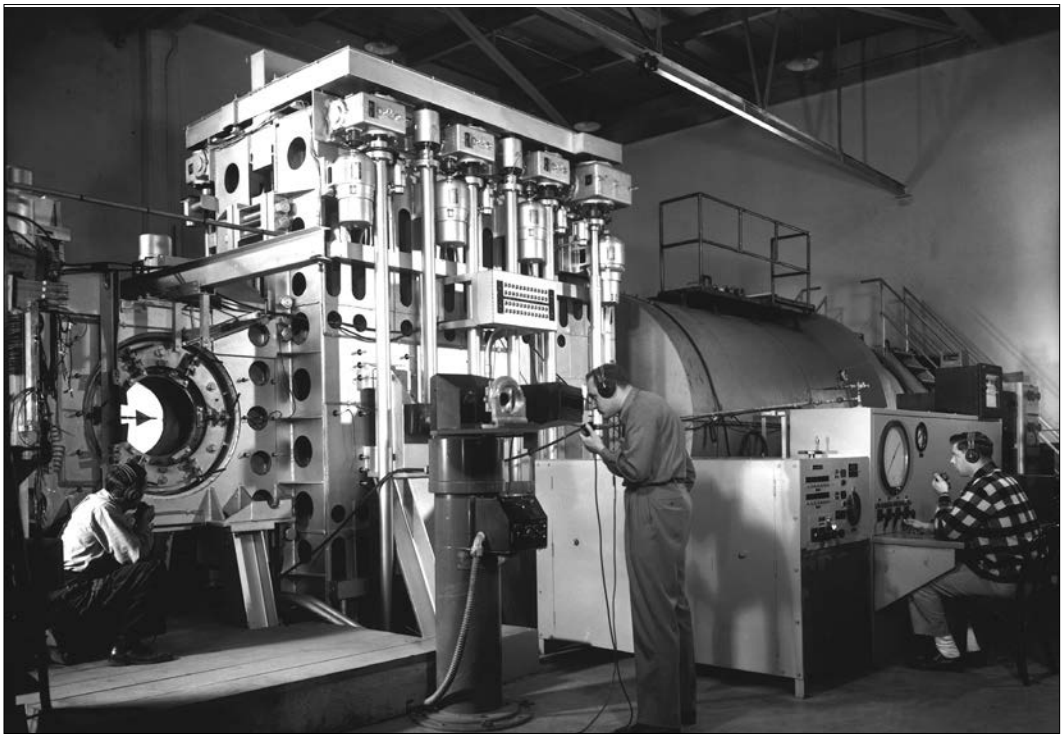
This plan view shows the 1- by 3-Foot ST No. 1 in the main portion of Building N-207 after the addition of the fifth compressor, aftercooler, and bypass duct. The cooling tower served both coolers. Note the 1- by 3-Foot ST No. 2 in the N-207A wing at upper right. (Image credit: NASA TM-102838, Fig. 8)



The Propulsion Simulator Calibration Laboratory conversion replaced the 1- by 3-Foot Supersonic Tunnel No.1's aftercooler, nozzle, and test section with a calibration tank and utilized the tunnel's compressor array as a vacuum system to maintain a low pressure in the calibration tank during the operation of CMAPS air-powered model engines. The 1- by 3-Foot ST No. 1's cooling tower (not shown) served the "water cooler." (Image credits: AIAA 82-0574, Fig. 7 and AIAA 82-0574, Fig. 8)



1- BY 3-FOOT SUPERSONIC TUNNEL NUMBER 2



This view of the 1- by 3-Foot Supersonic Tunnel No. 2 in 1948 shows the entire tunnel except its diffuser and exhaust, which are out of the photo to the left. The flexible-wall nozzle dominates this scene, with the test section to its left, and the settling chamber behind the control console to its right. Drawings in the 1- by 3-Foot Supersonic Tunnel Number 1 listing show how both tunnels were oriented in Building N-207. (Photo credit: NASA A-13011)

SIGNIFICANCE

The 1- by 3-Foot Supersonic Tunnel Number 2 (1- by 3-Foot ST No. 2) was the first supersonic wind tunnel at Ames, the first of this size, and likely the first to successfully use a variable-contour nozzle to permit the test speed to be changed. It was built using money from the authorization for the 1- by 3-Foot Supersonic Tunnel Number 1 (1- by 3-Foot ST Number 1) that was saved through careful project management, making it an excellent example of the ingenuity displayed by Ames's managers and engineers to obtain the greatest value from the available funds.

DESCRIPTION

The 1- by 3-Foot ST No. 2 was an open-circuit, supersonic, blowdown tunnel employing either a fixed or a variable-wall nozzle that utilized compressed air at up to 88 psi from the 12-Foot Pressure Wind Tunnel (12-Foot PWT), located next door, in an open circuit to the atmosphere, providing a maximum pressure differential across the 1- by 3-foot tunnel of approximately 75 psi. A steel pipe ran above ground from the 12-Foot PWT to Building N-207 and through its west wall to supply the 1- by 3-Foot ST No. 2,

which occupied a 60- by 50-foot wing (N-207-A) on the southwest corner of the building. The tunnel consisted of a cylindrical settling chamber; the nozzle assembly; a test section with circular, optically clear windows suitable for schlieren photography; an 80-foot-long diffuser that penetrated the wing's east wall; and a vertical exhaust stack, giving it a total length of approximately 125 feet. A console next to the settling chamber contained the tunnel's operating controls, and a large, multiple-manometer panel near the test section provided pressure measurements.

The 1- by 3-Foot ST No. 2 shared nozzles with the continuous-flow 1- by 3-Foot ST No. 1. They employed one of two fixed nozzles designed for specific speeds, or a flexible-wall nozzle that could be reshaped to obtain a range of supersonic Mach numbers. Eight electric motors, four per side acting through reduction gearboxes, turned jackscrews that altered the shape of flexible top and bottom plates to recontour the nozzle for the desired Mach number. The sidewalls were fixed in place. The Southwark Division of the Baldwin Locomotive Works fabricated all of these nozzles, which were fully interchangeable between the two tunnels. Since run time was limited in the 1- by 3-Foot ST No. 2, nozzle adjustments were made only between runs. When installed in the 1- by 3-Foot ST No. 2, the variable-speed nozzle provided a Mach number range of approximately 1.2–3.4. Exhausting to atmosphere, the 1- by 3-Foot ST No. 2 was not pressurized in the classic sense, but the pressure of the air entering the settling chamber could be controlled to yield some variation in Reynolds number.

The 1.0- by 2.8-foot test section was equipped with an optically clear circular window on each side to permit schlieren photography. These windows were mounted in doors that provided access to the model. Most models were sting-mounted and utilized internal strain gages to sense force and moment data, and the large manometer panel provided pressure measurements at multiple points. A camera photographed the panel during test runs for later data takeoff and analysis.[64]

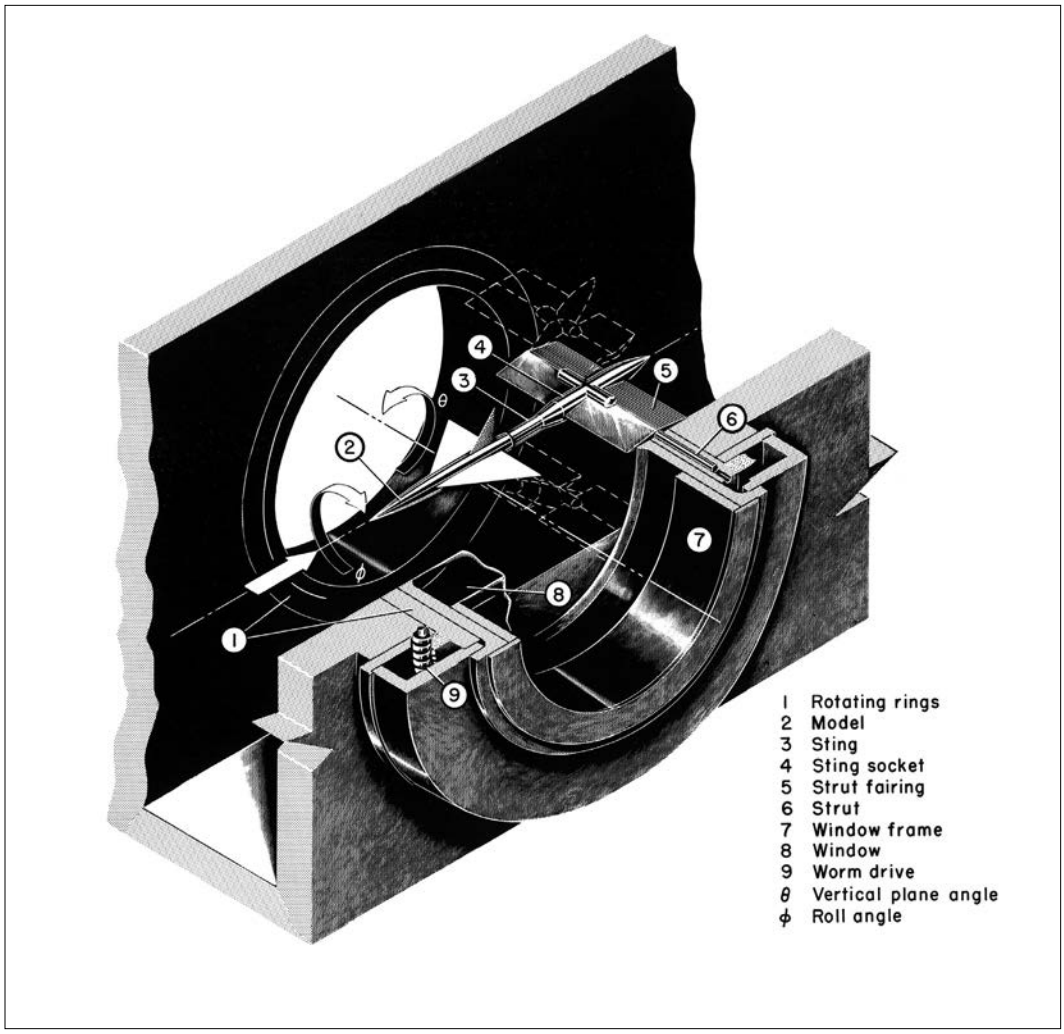
HISTORY

As discussed in the 1- by 3-Foot ST No. 1 section, plans for the Ames Aeronautical Laboratory had included supersonic facilities from its inception, but wartime priorities initially prevented construction of them. By 1944, as the war moved toward its conclusion, $1.25 million had become available, and Ames began building a 1- by 3-foot tunnel. Led by H. Julian "Harvey" Allen, head of the Theoretical Aerodynamics Section, Ames engineers realized the budget might be adequate for them to build not one, but two 1- by 3-foot tunnels by using compressed air from the 12-Foot PWT to power one of them. This was a classic NACA "bootleg" affair, a technique new to Ames, though time-honored at Langley. Nevertheless, it produced a second tunnel that the engineers put into service quickly to gain some sorely needed experience. Both tunnels were completed within the allotted budget by August 1945, although it took the engineers several more months to fully debug them.[65]

The two 1- by 3- foot tunnels used interchangeable nozzles. Since the 1- by 3-Foot ST No. 2 was not pressurized and did not employ nozzle adjustment while running, it was spared some of the problems that initially plagued the variable-speed nozzle in the 1- by 3-Foot ST No. 1. For example, the joints between the flexible and fixed walls leaked far less when not under pressure. Still, it was not immune from difficulties, and the fixed nozzles did see run time in the blowdown tunnel, though much less than in the closed-circuit, pressurized one. While the engineers could only deal with the leakage problems in the pressurized tunnel, they learned a great deal about how precisely the nozzle contour had to be set in the 1- by 3-Foot ST No. 2. This benefited both 1- by 3-foot tunnels, and it informed the designs of other flexible-wall and sliding-block nozzles that would be used in subsequent supersonic tunnels at Ames and elsewhere. Even after the difficulties with the flexible-wall nozzle had been largely resolved, much of the research work done in the 1- by 3-Foot ST No. 2 was accomplished with one of the simpler, fixed nozzles.

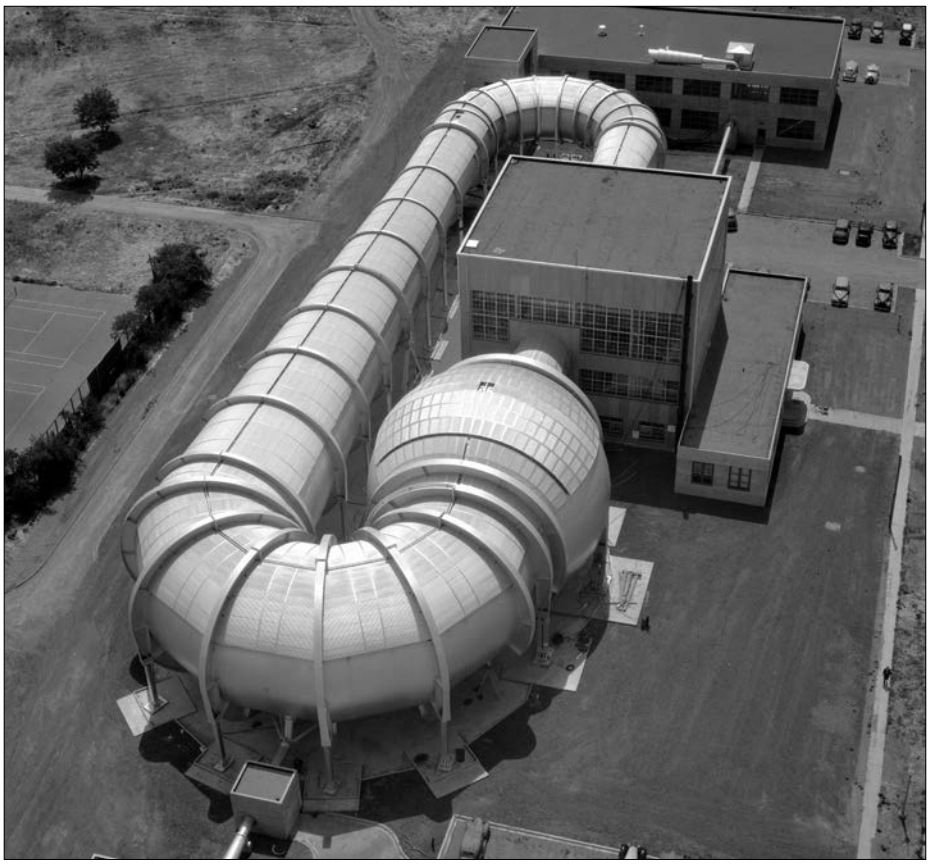
In addition to being a tool for giving engineers, operators, and researchers experience with a variable-speed supersonic tunnel, the 1- by 3-Foot ST No. 2 hosted a number of significant projects that investigated the fundamental principles of supersonic flow. Some of these were purely empirical experiments, while others sought to identify important design characteristics for supersonic aircraft or reconcile the still-developing theories about supersonic flow with empirical data. While the 1- by 3-Foot ST No. 2 labored largely in obscurity on seemingly mundane programs, the knowledge gained was crucial to mastering the supersonic flight regime.[66]

Since the 1- by 3-Foot ST No. 2 was a "bootleg" project, available records of it are, not surprisingly, scarce, and none specify exactly when it was abandoned and dismantled. It seems likely that it was dismantled when the 1- by 2-Foot Free-Flight Tunnel, which also used air from the 12-Foot PWT, was built next to Building N-207, or when the 1- by 3-Foot ST No. 1 was converted into the PSCL. Historian Alex Roland did not list it in his 1985 book, *Model Research*, implying that it had likely been demolished before then. The room it occupied currently houses the Wind Tunnel Balance Calibration laboratory and a portion of the Wind Tunnel Compressor Blade refurbishment and storage facility.[67] The only remaining trace of the 1- by 3-Foot ST No. 2 is a filled-in circular hole in the west wall where the air supply pipe had entered. No portion of the tunnel is known to have survived.



Since they used interchangeable test sections, both 1- by 3-foot supersonic tunnels employed the sting arrangement shown here. Note that the strut is attached to dual rings around the observation windows that rotate, turned by a worm-gear drive, to set the desired pitch. (Image credit: NASA A-21506)

12-FOOT PRESSURE WIND TUNNEL



This 1946 aerial view of the 12-Foot Pressure Wind Tunnel shows the awning over the circuit and the horizontal vacuum ejector exhaust on the roof of the auxiliary building. The pipe in the left foreground conveyed the tunnel's compressed air to power the 1- by 3-Foot Supersonic Tunnel No. 2 and the Supersonic Free-Flight Tunnel located in adjacent buildings. (Photo credit: NASA A-9939)

SIGNIFICANCE

The 12-Foot Pressure Wind Tunnel (12-Foot PWT) was the first tunnel to combine pressurization to achieve high Reynolds numbers with low-turbulence features and near-sonic speed in a large test section. With its variable pressure and speed capabilities, Mach and Reynolds numbers could be adjusted independently of one another to achieve a wide variety of test conditions.

DESCRIPTION

The 12-Foot PWT, Ames's Building N-206, is a variable-pressure, single-return, closed-circuit wind tunnel measuring approximately 300 feet long by 100 feet wide, not including its office building or Building N-206-A, which houses the tunnel's drive and compressor equipment. Externally, it exhibits a circular cross section around its entire

circuit. Its most recognizable features are its 180-degree turns and a large spherical bulge that forms the settling chamber enclosure immediately ahead of the test section enclosure.

The 12-Foot PWT's circuit was fabricated from steel plate up to 2 inches thick, with external "T" and "L" section structural hoops. Most of these structural hoops have integral columns that transmit the tunnel's weight to concrete foundations. The columns and associated foundations were designed to carry the weight of water for a full tunnel hydrotest.[68] The tunnel features unusual gored turns at both ends that turn approximately 180 degrees. The turn downstream from the test section on the tunnel's west end has eight segments, while the larger-diameter east end turn utilizes only seven, making the angle between any two adjacent segments about 22.5 or 25 degrees respectively. Each joint has a set of turning vanes to stabilize the flow and prevent stratification of the flow. As with most modern tunnels, the 12-Foot PWT's diameter gradually increases through the circuit, from 12 feet at the test section exit to about 42 feet at the entrance to the settling chamber. The spherical settling chamber enclosure is an unusual design, and its size dictated the tunnel's centerline placement at approximately 30 feet above the ground. Inside the 63-foot-diameter spherical bulge is a settling chamber that contains multiple anti-turbulence screens and a water-cooled heat exchanger to remove compression heat generated by the fan during operation. A 25:1 contraction cone connects the settling chamber to the test section. The tunnel was welded according to pressure vessel welding code to maintain pressure integrity. The tunnel was originally equipped with a sheet metal awning that shielded most of the circuit from solar heat, and beneath it was a system of pipes and nozzles that sprayed water on the tunnel shell for cooling. It and the tunnel shell were painted white to further reduce solar heat gain. While the tunnel remains white, the water nozzles and the awning were removed during the 1990s.[69]

The original test section measured 12 feet in diameter, though flat fairings on the walls, floor, and ceiling reduced the vertical and horizontal dimensions to approximately 11.25 feet. Its useful length was 18 feet. Both sting and floor model mounts were available, and the floor included a 4-foot-diameter turntable that was most often used with bipod mounts for low-speed testing, but also occasionally with semispan models.[70] A trunnion-type mount was also available for tests of airfoils that spanned the test section. The test section was enclosed in a 27-foot, 6-inch-diameter cylindrical pressure vessel with external strengthening rings and end beams. This cylinder was an integral part of the tunnel's pressure shell that was designed to operate at pressures between 2.5 and 75 psia. Uniquely, the test section's centerline was 6 feet, 6 inches above the cylinder's centerline to provide space within the pressure vessel for the mechanical balance frame and scale system, plus the sting's pitch drive. An 8-foot-diameter airlock opened into the shop area outside the pressure cylinder, but access was possible only with the tunnel near atmospheric pressure. The tops of the test section and cylinder had 5- by 11-foot hatches for installing models, which were handled by a 7.5-ton overhead bridge crane.

The 12-Foot PWT was also equipped with a dynamometer for testing propellers. This dynamometer was installed in the original test section when needed, and it contained

isolation mounts to minimize external influences on tests. The heart of the device was a 1,000-horsepower, variable-speed electric motor that turned a propeller shaft, upon which a wide variety of propellers and spinners could be fastened. Its speed was infinitely variable up to 6,600 revolutions per minute. Various cowlings could also be mounted to replicate the configuration immediately downstream of the test propeller. Strain gages affixed to thrust bearings and electrical torque sensors furnished the primary data, though additional instrumentation could be used to measure pressures and other parameters. By using an optional internal gearbox, the dynamometer could test dual, counter-rotating propellers.[71]

The test section and pressure cylinder were originally housed within a cubical masonry building approximately 70 feet square by 60 feet high. A large portion of all four sides consisted of steel-framed, multipaned, industrial-style windows that admitted natural light into the interior's three levels. The first floor matched the elevation of, and was connected to, a single-story office building designed in a style similar to that of the test section enclosure building. This office building was on the tunnel's north side. The test section enclosure building's second floor, which was 12 feet above the first floor, provided space for the model-preparation shop, and its third floor, 18 feet above the second, supported the control area. Openings in the floors allowed the overhead crane to lift models between floors as necessary.

In the mid-1980s, the entire tunnel shell was condemned by the pressure vessel staff due to extensive flaws in the shell steel welding. These were likely flaws that had existed from construction. Ames performed an extensive reconstruction of the 12-Foot PWT between 1990 and 1994 to correct a major pressure shell design error that subsequently resulted in numerous material flaws in the skin.[72] While this reconstruction accomplished a number of objectives, including a complete replacement of the tunnel's pressure shell, the installation of modern instruments and data acquisition equipment, an increase in power, and the replacement of the original office and test section enclosure buildings with larger, metal-skinned structures, it also addressed the continuing difficulties inherent in installing, adjusting, and servicing models in the original test section. Personnel access was through the inconvenient airlock, and the entire tunnel had to be depressurized each time access was needed. The original test section was replaced with one measuring 12 feet in diameter by 28 feet, 6 inches long, and it was installed inside a new spherical pressure shell with three circular openings. In its operating position, the test section lined up with two of these openings and the rest of the tunnel circuit. For model access, the test section rotated 90 degrees within the sphere to align one end with the third opening to the shop area. Hatches called isolation valves sealed the tunnel circuit so that the sphere alone could be depressurized. Then an access valve could be opened to furnish direct access to the test section from the shop area. This arrangement made access far more convenient and reduced subsequent pumping time, resulting in a substantial improvement in operating efficiency.[73]

The original design for the settling chamber was essentially retained, but it was enlarged to 68 feet in diameter, and a heat exchanger coil was installed to replace the external cooling system that sprayed water on the tunnel's shell.[74] The modifications also included the replacement of the massive makeup air compressor and related piping; the addition of heated, high-pressure air capability to power turbine-powered engine simulators; the installation of new rear strut, floor turntable, and under-the-floor arc sector model supports; the addition of a tie line to the UPWT that enabled the compressors at each tunnel to support one another; and the addition of a machine shop and two model preparation rooms.[75]

The 12-Foot PWT's 28-foot-diameter two-stage axial-flow fan is located just after the first 180-degree turn, with their hubs and shaft housed within a streamlined nacelle. The drive shaft extends from the front of the nacelle, through a sealed port in the tunnel's shell, and into Building N-206-A, an L-shaped masonry building on the tunnel's west end, where it was originally connected to two 6,000-horsepower variable-speed motors. This arrangement was replaced with a new 15,000-horsepower synchronous motor driven by a variable frequency load commutated inverter. This drive could generate a maximum speed of about Mach 0.98—somewhat less with a model installed. Building N-206-A also houses the 50,000 cubic-feet-per-minute air compressor used to pressurize the tunnel.

HISTORY

The 16-Foot High-Speed Tunnel (16-Foot HST) and 40- by 80-Foot Full-Scale Tunnel (40- by 80-Foot FST) had given Ames impressive capabilities by the end of World War II, but both were atmospheric wind tunnels. With its large size, the 40- by 80-Foot FST could achieve flight-level Reynolds numbers, but only at low speeds. The 16-Foot HST could approach Mach 1, but it could not accept full-size aircraft, so its Reynolds numbers always ran below those of actual flight. Since it opened the Variable Density Tunnel (VDT) in 1922, the NACA's Langley Laboratory had been using pressurization to raise Reynolds numbers and correct for "scale effect" in tunnels as large as 19 feet in diameter, but none of these tunnels exceeded 330 mph. Turbulence in the airflow caused by tunnel walls, corners, and protrusions introduced disturbances that increased with speed, so Langley also built a prototype Low-Turbulence Tunnel (LTT) and then its Low-Turbulence Pressure Tunnel (LTPT) to explore methods of turbulence reduction. They accomplished their goal, but only with small, two-dimensional test sections. The 19-Foot Pressure Tunnel followed, but airplanes flying when it opened already surpassed its 330-mile-per-hour top speed. In spite of the evident need for combining pressurization, low turbulence, and high speed in a tunnel large enough to accommodate reasonably sized models, the task's complexity was a challenge not tackled until about 1939.

Various Langley and, later, Ames engineers began to tackle the complicated task and decided that such a tunnel operating at a maximum of 6 atmospheres (88 psia) was feasible, and the NACA's general committee decided to build it at Ames. Carlton

Bioletti, a Langley transfer, led the design effort, assisted by other Langley transfers and some young engineers recruited from nearby Stanford University. One of these, Walter Vincenti, a student of renowned structures engineer Stephen P. Timoshenko, performed most of the complex thick-wall stress analysis of the tunnel's pressure shell, consulting Timoshenko on numerous occasions. The decision to use gored turns instead of conventional 90-degree turns was primarily to reduce stress at the joints, though it provided some turbulence minimization benefits as well.[76]

Langley engineers had identified two design elements that substantially reduced the inevitable turbulence when installed immediately upstream of the test section. They installed very large settling chambers in their LTT and LTPT to get inlet nozzles with high contraction ratios—the ratio of the settling chamber cross-sectional area to that of the test section—that improved, but did not completely solve, the problem. For further improvement, they adopted some British findings and installed multiple screens woven of thin phosphor bronze wire in the settling chamber. At the low air speed in the chamber, the resistance posed by these screens all but eliminated turbulence. Bioletti and his staff determined that no fewer than eight screens would be needed to achieve the smoothness of flow they desired in the 12-Foot PWT. Designing a frame to hold these screens proved to be a challenge in itself, but one that they met.

Langley engineers had hydrostatically tested[77] models of the gored turns to validate their LTPT design, but for the larger and heavier 12-Foot PWT, the Ames engineers felt that a hydrostatic test of the completed pressure shell was the only way to ensure that it could not fail—possibly in a catastrophic explosion. The tunnel structure and foundations had to be designed for this from the start, since filling it would take 5 million gallons of water weighing almost 21,000 tons, far more than the tunnel itself weighed. Filling it took a week. It was, however, a wise decision, because a welded joint ruptured during the first hydrostatic test before it reached the required 9 atmospheres of pressure. No additional damage or injury occurred. Repairs were soon made, and the tunnel passed its second test.[78]

For the 12-Foot PWT, engineers and researchers wanted the highest speed possible. The 16-Foot HST and others had demonstrated that Mach 1 was the theoretical maximum for a non-supersonic tunnel, and the slotted wall for stable transonic operation had yet to be invented. Thus, the drive fans and motors were selected to obtain speeds of up to Mach 1. The best arrangement was a pair of 6,000-horsepower, variable-speed motors turning two fans. The fans were placed in a nacelle after the first 180-degree turn, but the motors were located in an adjacent building. The arrangement generated speeds of up to Mach 0.98 with the test section empty, but most tests ran no higher than about Mach 0.9. This auxiliary building also housed the compressor and dehumidifier needed to pressurize the tunnel and a steam ejector to reduce its pressure below atmospheric when desired.

With a 12,000-horsepower drive, removing the compression heat was essential, and the designers used a rather crude but effective system previously used at Langley. They

installed an awning over most of the circuit and placed pipes under it with nozzles that sprayed water over the top of the tunnel's shell. It drained down the side and fell into a catch basin, taking heat with it. The awning also reduced the solar heat load.[79]

The 12-Foot PWT first ran in July 1946, and it entered service as soon as calibration tests demonstrated that the high-speed, low-turbulence, and pressurization concept worked as designed. Researchers made good use of these capabilities throughout the next four decades with programs that delved into numerous aspects of flight at high Reynolds numbers. Some of the most significant early programs used the propeller dynamometer to investigate the performance parameters of both single and counter-rotating propellers with a variety of spinners and turboprop engine cowlings. Other programs pointed to major advances in straight, swept, and delta wings, particularly in such areas as conical camber for delta wings and multi-part flap systems. Flap-development work in particular continued throughout the tunnel's active life.[80]

While the 12-Foot PWT's capabilities made it a valuable and well-utilized research facility, it had a serious design flaw. The steel used for its construction had a low ductile-to-brittle transition temperature, similar to the problem in the Liberty Ships during World War II. This transition temperature was near the minimum ambient temperatures experienced at Ames on cold winter nights and resulted in numerous flaws that threatened the viability of the vessel. Specific flaws were subsequently determined to be several feet long. The only solution was replacement of the pressure vessel shell using a modern steel with superior properties.[81]

About 1986, engineers at Ames concluded that a total reconstruction of the tunnel using new steel was necessary if the tunnel was to remain in service. Redesign of the new pressure shell was done with American Society of Mechanical Engineers (ASME) alternative design rules allowing for optimization of shell thicknesses. The test section was completely redesigned with a rotating segment that could be isolated from the tunnel circuit using a set of three autoclave hatches. This allowed for test section access while only blowing down the isolation sphere to get to atmospheric pressure. The tunnel circuit remains pressurized during test section access, allowing for short pumping times to bring the facility back to test conditions. This resulted in a major increase in productivity during operations.[82]

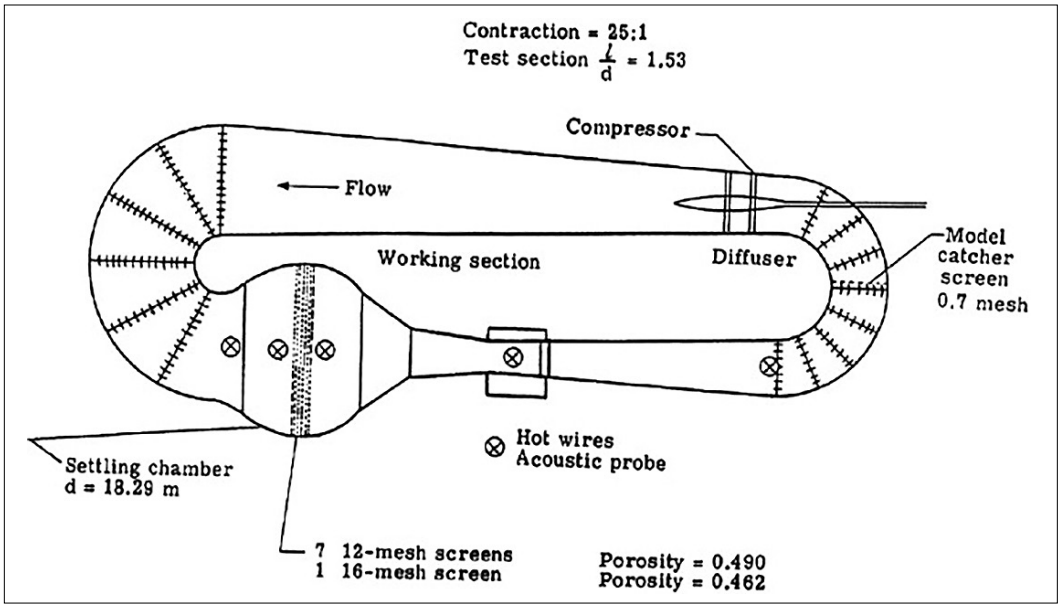
While these two items resolved the most serious problems, the engineers also replaced the dual drive motors with a single15,000-horsepower induction motor and variable-frequency speed control, installed modernized instrumentation and data acquisition equipment, and replaced the shop and office buildings with larger structures that furnished improved shop facilities. The shop improvements included an improved shop on the test section (second) floor of the facility as well as two model preparation rooms on the ground floor equipped with model supports, instrumentation racks, and a complete data acquisition capability identical to those housed in the new second-floor control room that served the test section.[83] Thus, models could be set up and fully

calibrated before they were moved into the test section, a feature that saved time and improved accuracy.

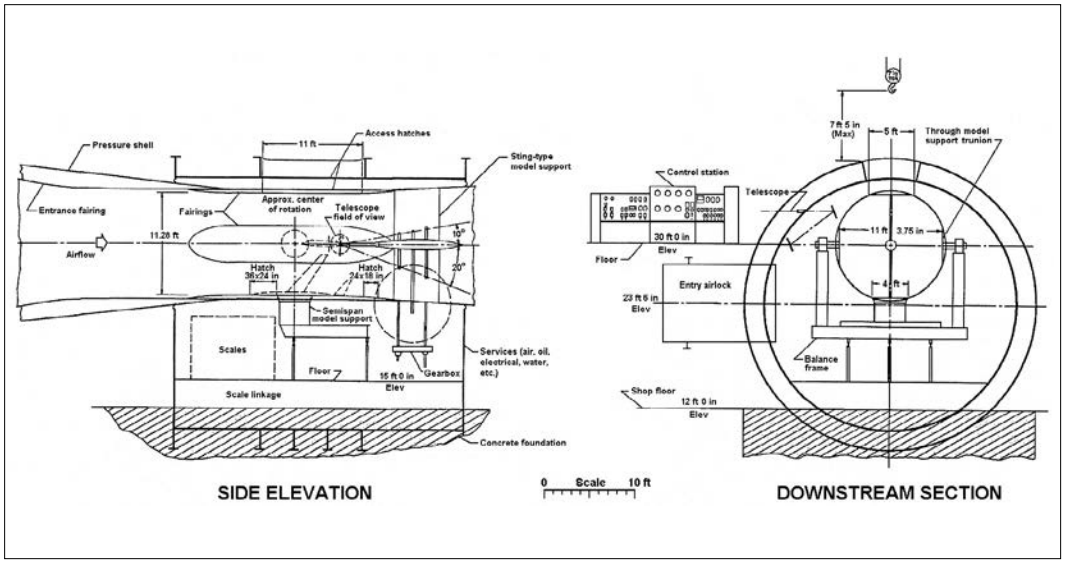
After the five-year project, the 12-Foot PWT reopened in August 1994. Technically, the project produced an excellent facility, but the investment did not produce the expected dividends. During the 10-year construction period, there was a decreased industry need for subsonic testing that all but eliminated the 12-Foot PWT's customer base. The tremendous cost of new airplanes, coupled with the recent end of the Cold War, had drastically reduced new aircraft programs, and aircraft manufacturers were in the midst of a merger process that ultimately resulted in three primary defense contractors and one builder of large commercial airliners in the United States. One of the survivors who had been a major user of the 12-Foot PWT had begun using a foreign tunnel during the 12-Foot PWT's outage, and it chose to continue that after the Ames tunnel reopened. The surviving manufacturers also found they could use their own tunnels more effectively, especially since the rapid rise of computational fluid dynamics (CFD) computer software had sharply reduced the number of hours needed for wind tunnel testing. On top of this, NASA had instituted a "full cost recovery" policy throughout the agency in an attempt to have outside customers pay all operating costs for facilities like wind tunnels. With other options for doing less development work, the outside customers disappeared. The slowdown of new aircraft development projects also reduced the need for aeronautical research projects within NASA and specifically Ames as well, and NASA's budget priorities were elsewhere. In May 2003, Ames decided to cease operations in the 12-Foot PWT, and it was placed in "mothball" status in September 2004. Thus, it remains intact, but currently unused.[84]

After reopening the facility in 1994, the facility was further optimized to support large, TPS-powered, semispan models by creating a large image plane, removing the large rear strut model support to minimize interference, and creating several high-capacity balances to support future semispan testing. There have been efforts in recent years to prepare the 12-Foot PWT to be a Propulsion Simulation Calibration Facility. To date, this has included a replacement of the facility control system, an overhaul of the control room, an updating of the control room instrumentation and data system, and the restoration of a high-pressure air heater.[85]

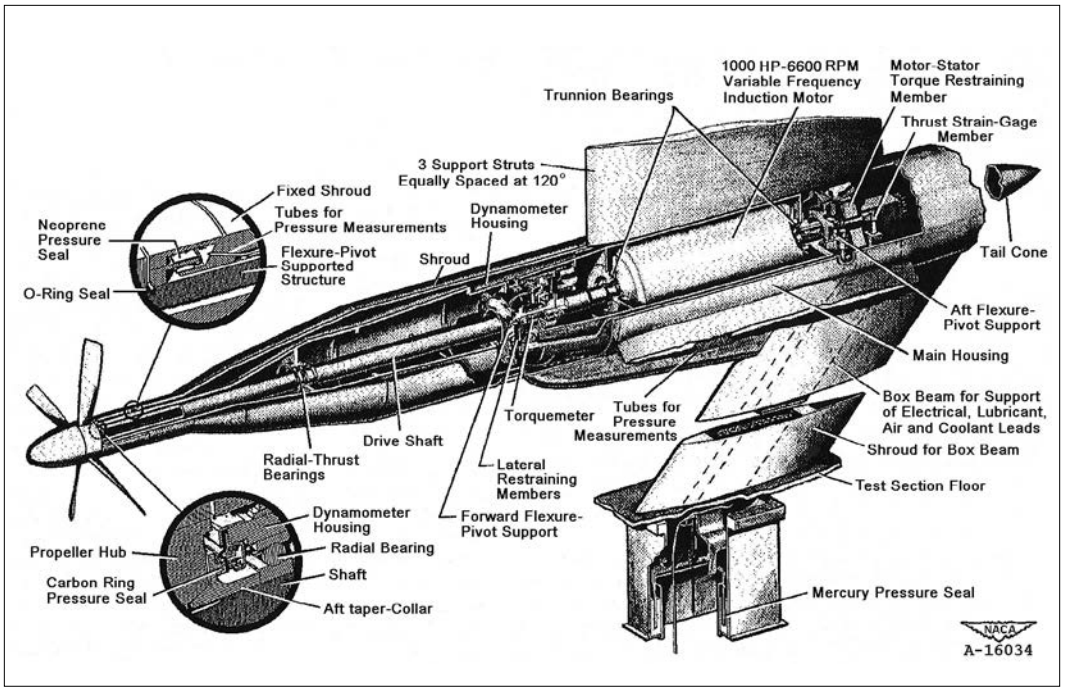
The 12-Foot PWT's model preparation rooms remain in service. When Ames elected to rebuild the 12-Foot PWT, other capital projects went unfunded, including an upgrade of the instrumentation racks at the Unitary Plan Wind Tunnel (UPWT) similar to that done at the 12-Foot PWT. At the 12-Foot PWT's deactivation in 2004, the UPWT was the only tunnel at Ames with a viable customer base, though one of its three test sections had also been closed, and it lacked the modern setup and calibration equipment. Since the data acquisition systems of the two facilities were by then compatible, models destined for testing in the UPWT are now prepared and fully calibrated in the 12-Foot PWT's model calibration rooms before being transferred to the UPWT.



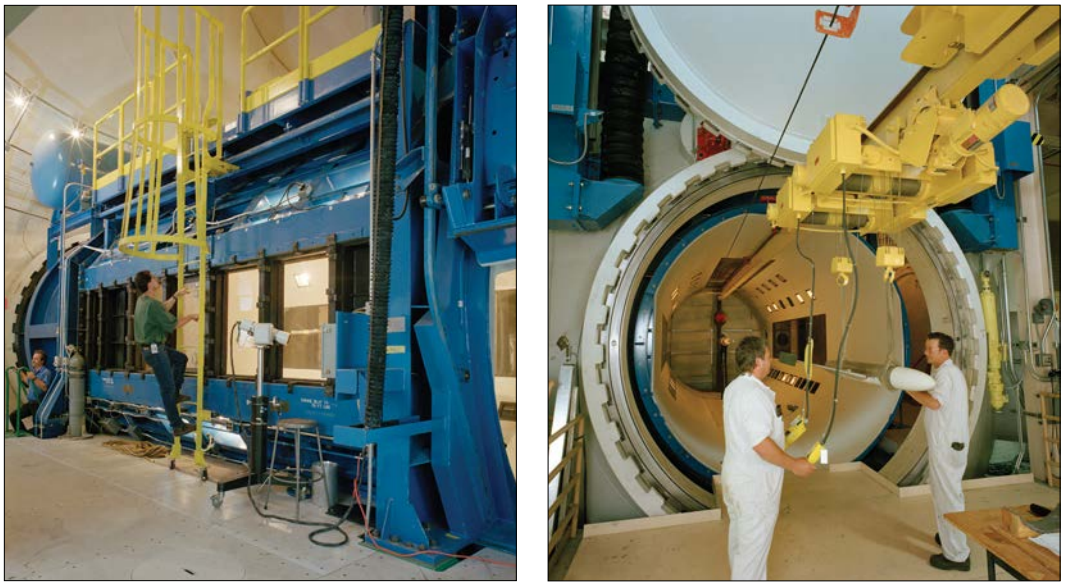
This plan view of the 12-Foot Pressure Wind Tunnel shows its configuration following the 1994 reconstruction that gave it a larger motor and a new test section. The inset shows an all-new pressure vessel, an internal heat exchanger, and the way the test section rotated for model access while the isolation valves sealed the remainder of the circuit so that it could remain pressurized during adjustments to a model between runs. (Image credit: AIAA 96-2204, Fig. 1)



This drawing shows the 12-Foot Pressure Wind Tunnel's original test section and its location within the cylindrical pressure shell. The entire balance system was inside the pressure shell. (Image credit: NASA TM-80995, Fig. 2)



This 1,000-horsepower propeller dynamometer was used in the 12-Foot Pressure Wind Tunnel to test the performance and efficiency of propeller and spinner designs at speeds of up to 6,600 revolutions per minute. An optional gearbox (not shown) permitted dual, counter-rotating propellers to be tested. (Image credit: NASA A-16034)



These two 1995 views show the 12-Foot Pressure Wind Tunnel's modernized test section in its run (left) and access (right) positions. In the run view, airflow is from left to right. Note the lugged rings that rotated to seal the valves closed. The monorail hoist eased model handling. (Photo credits: NASA AC95-0203-035 and NASA AC95-0203-037)

Here an early MD-11 model has been mounted on a pylon in 1996 for testing in the modernized 12-Foot Pressure Wind Tunnel. The aft pylon controlled the model's angle of attack. (Photo credit: NASA AC96-0071-6)

This 1995 evening view of the modernized 12-Foot Pressure Wind Tunnel has the historic area of Moffett Field as a backdrop. (Photo credit: NASA AC95-0203-019)

6- BY 6-FOOT SUPERSONIC TUNNEL

This view of the 6- by 6-Foot Supersonic Tunnel from the roof of the Full-Scale Tunnel about 1950 clearly shows the cooling coil bulge and some of its piping to the redwood cooling tower. Note the drive motor housing and dry air sphere on the far side of the tunnel. (Photo credit: NASA A-13548)

SIGNIFICANCE

The 6- by 6-Foot Supersonic Tunnel (6- by 6-Foot ST) was the NACA's first large supersonic wind tunnel and the first to utilize both an axial-flow compressor and a sliding-block nozzle to change the Mach number. It also pioneered the NACA's use of automated data acquisition systems with equipment that monitored and processed data from eight points. In service for four decades, the 6- by 6-Foot ST hosted tests of almost all first-generation American supersonic airplanes and missiles during the 1950s. Following its closure, the tunnel became the home of an educational program known as the Ames Aerospace Encounter.

DESCRIPTION

The 6- by 6-Foot ST is a closed-circuit, single-return, supersonic wind tunnel constructed of steel plate with circumferential support rings. While no longer operated, an eight-stage axial compressor powered by two 30,000-horsepower synchronous motors mounted in tandem on a common drive shaft drove it during its service life. Speed control was accomplished using an asymmetrical, sliding-block nozzle that translated along the tunnel's centerline to vary the height dimension of the two-dimensional nozzle's throat. This arrangement produced Mach numbers between 0.6 and 2.2 in the 6-foot-square,

14.4-foot-long test section. Pressure within the tunnel could be controlled from approximately 0.3 to 1.1 atmospheres (4 to 16 psia).[86]

Ames numbered the complex N-226. A two-story concrete building with modern detailing on the tunnel's east side housed offices, model shops, compressors, and vacuum pumps that supported its operations. The high-bay center portion of this building enclosed the test section and control room area on its second floor. All walls have several multipane windows arranged in a regular order. Two sets of personnel doors on the east (front) side provide entrance to the north and south wings, and a large double door opens into the model shop on the first floor of the recessed, central portion. Another large roll-up door on the north end furnishes access to the compressors and vacuum pumps. The compressors delivered air to air dryers, which lowered the water content to about 0.0003 pound of water per pound of air, and on to a 60-foot-diameter storage sphere located west of the building's north end. Operators used this dry air to purge the tunnel before test runs and to replace any losses during the runs.[87]

The 6- by 6-Foot ST's two 30,000-horsepower drive motors are housed in an elevated enclosure next to the tunnel's northwest corner (Corner 2). The motors are mounted on a concrete pedestal that locates the drive shaft at the tunnel's centerline height, and a metal enclosure protects them from the weather. They turned an eight-stage, axial-flow compressor located approximately 50 feet downstream from Corner 2.

Approximately 60 feet beyond the compressor, a large bulge houses a multi-row cooling coil to remove compression heat. Water circulated through a six-cell cooling tower constructed of redwood, located immediately west of the tunnel, which transferred this heat to the atmosphere. This system maintained a maximum temperature of about 115°F in the tunnel.

The 6- by 6-Foot ST is equipped with a variable-geometry nozzle developed at Ames. It employs an asymmetric nozzle with a contoured sliding block for its floor; a fixed ceiling with a different contour; and fixed, parallel sidewalls. An electric motor, acting through a gearbox, turns a lag screw to move the sliding block longitudinally. As it advances, the nozzle's throat area decreases while the length of its expansion section increases, thus raising the Mach number it generates. The nozzle can be adjusted during operation to produce any Mach number between 0.6 and 2.2. A settling chamber that also functions as a transition from the circular duct to the rectangular cross section of the nozzle immediately after Corner 4 precedes the nozzle. The diffuser between the test section exit and Corner 1 also transitions from a square to circular cross section.

The 6- by 6-Foot ST's test section featured four 46-inch-diameter windows, two per side. One pair of these was optically clear and precision-ground to support schlieren photography, since a schlieren apparatus was part of the tunnel's original equipment. The other pair of windows allowed test personnel to observe the model during testing. Most models were sting-mounted, and the sting support could vary the model's pitch between –18 and +13 degrees. Special stings could also provide up to ±10 degrees of yaw, or models could be mounted vertically to make the pitch adjustment function in the

yaw axis. The tunnel featured a novel air injection system that extracted air from the return duct after Corner 3 and injected it into the diffuser entrance along both sides. Eleven-foot-long flaps set the taper of the diffuser's sidewalls and regulated the injection air. The constriction formed a second minimum that anchored the deceleration shock wave. A boundary layer extraction system added in 1956 could be employed to remove air from floor and ceiling slots to minimize turbulence and allow the tunnel to operate in the transonic range.

Models generally incorporated strain gages into their sting mountings and, if required, other internal components, and these were connected to the NACA's first automated data acquisition system. This system collected raw data from up to eight strain gages, computed key coefficients, and plotted and/or typed them for later analysis. It could also record data from six additional sensors. Manometer boards could be connected to measure pressures at more than 500 points. Following common practice for the 1940s and 1950s, periodic photographs of these boards recorded the data, which were read manually. Improved pressure sensors and data acquisition equipment ultimately allowed pressures to be recorded automatically.[88]

HISTORY

Supersonic wind tunnels had been a part of plans for the NACA's Ames Laboratory since its inception, but the demands of World War II placed its early emphasis on subsonic research and development work to improve military airplanes as quickly as possible. By 1944, the situation had eased enough for Ames to seek funds for supersonic tunnels. They succeeded enough to put two 1- by 3-foot supersonic tunnels online as the war ended, but H. Julian "Harvey" Allen and his staff of the Theoretical Aerodynamics Section wanted a larger tunnel with greater capabilities, and they proposed such a tunnel to Headquarters as early as May 1944. Director of Research George W. Lewis realized the estimated $4-million cost of the tunnel had little chance of congressional approval, and he put the proposal and plans in a drawer. Although no documents substantiate the story, most sources claim the plans stayed hidden for months until Lewis received a visit from Rear Admiral D. C. Ramsey, chief of the Navy's Bureau of Aeronautics. Ramsey talked about the Navy's need for a supersonic tunnel and asked Lewis if the NACA had thought about building one. Lewis pulled the plans out of his drawer, and Ramsey asked what it would cost. Not fazed by the price, Ramsey replied that the Navy would provide the funds, which it did in January 1945.[89]

With funds in hand, Carlton Bioletti took charge of the tunnel's detailed design, but Harvey Allen made seminal contributions as well, in particular the asymmetrical sliding-block nozzle. Allen, familiar with the 1- by 3-Foot Supersonic Tunnel No. 1's flexible-wall nozzle problems and aware of some experiments Abe Silverstein was doing with a movable tapered plug to vary a circular inlet, conceived of the asymmetrical nozzle as an alternate way to reshape a supersonic nozzle. To validate the concept, he built a 2- by 2-inch prototype of the nozzle, followed by an 8- by 8-inch pilot tunnel

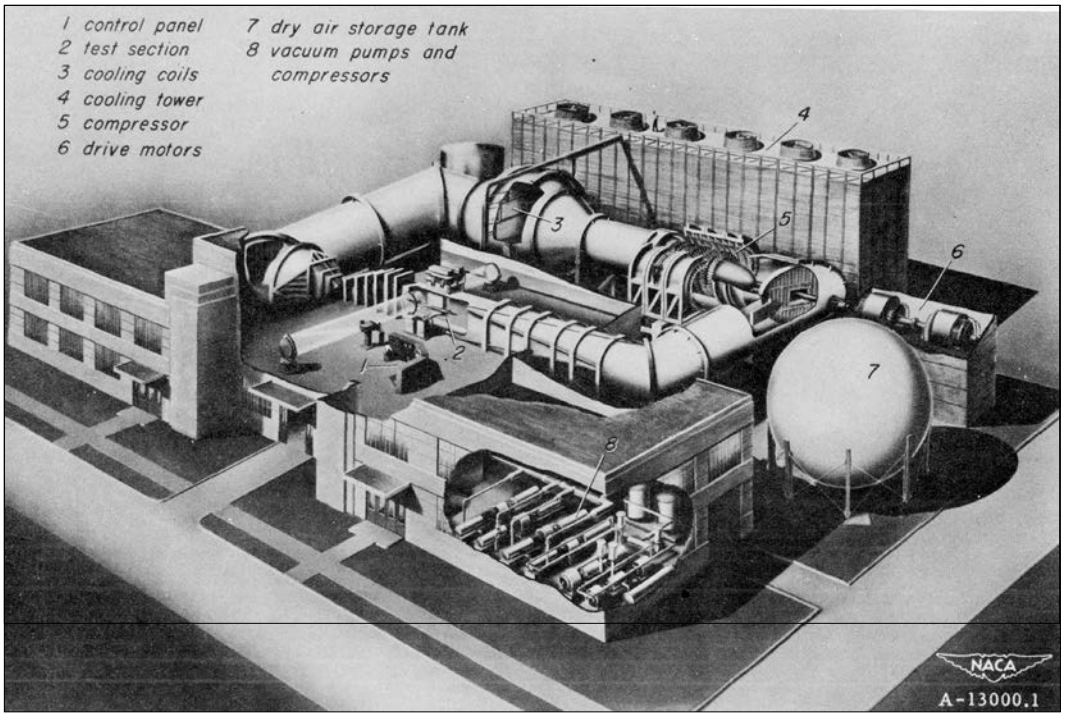
equipped with one that was powered with compressed air from the 12-Foot Pressure Wind Tunnel. Though not perfect, their success led to the design being included in the 6- by 6-Foot ST.[90]

Ames officials broke ground for the 6- by 6-Foot ST in May 1945, only a year after the original proposal. Construction proceeded at a reasonable pace and without major delays or incidents, even though the nozzle development and design were not completed until late 1945. Ames declared the 6- by 6-Foot ST operational on 16 June 1948, with Charles Frick in charge. There were, as expected, a few problems with the new nozzle design that Allen and his staff worked out, but the tunnel generally performed well from Mach 0.6 to 0.9 and between Mach 1.3 and 1.8. But like other high-speed tunnels of the time, it could not provide stable operation in the transonic range. Charles F. Hall studied the situation and ultimately modified the tunnel in 1956 to operate through the transonic range. His modifications, which included the addition of perforations in the test section's floor and ceiling, along with a boundary layer extraction system, also raised the top speed to Mach 2.2 and, under certain conditions, allowed speeds as low as Mach 0.25.[91]

During the 1950s, the 6- by 6-Foot ST was heavily booked with both basic research programs and development work for virtually every supersonic airplane and guided missile design produced in the United States, including the "Century Series" fighters and B-58 bomber for the Air Force and the Navy's F4D, A5J, and F8U. After the Unitary Plan Wind Tunnel entered service in 1955, aircraft development projects tended to use it, which allowed the 6- by 6-Foot ST to focus more on basic supersonic aerodynamics research.[92]

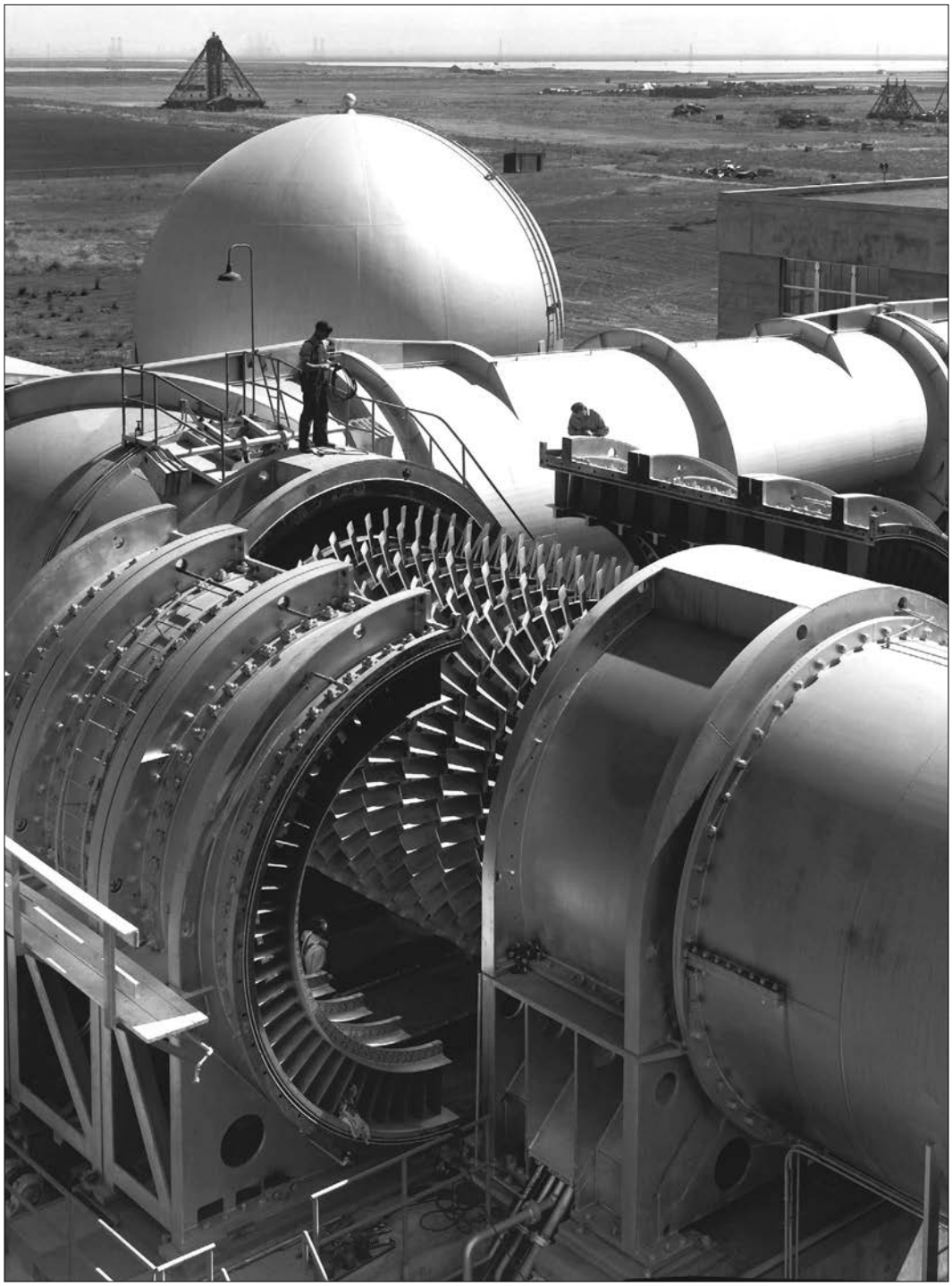
Mechanically, the 6- by 6-Foot ST changed little during its service career, with its only significant alterations being the modifications for transonic operation installed by Hall in 1956. Otherwise, the tunnel received periodic upgrades to its instrumentation and data acquisition system like many other NACA/NASA tunnels. Perhaps the most significant of these upgrades occurred during the early 1980s when F. K. Owen, G. M. Orngard, and T. K. McDevitt installed the first three-dimensional laser Doppler velocimetry (LDV) system to measure and better analyze complex flow fields.[93]

After four decades of service, Ames closed the 6- by 6-Foot ST about 1988, then reopened it in October 1991 as the site for the Ames Aerospace Encounter, a NASA-sponsored math- and science-based education program for students in grades 4–6. Though the tunnel was not operated, it was maintained intact and incorporated into the program. Thus, the 6- by 6-Foot ST continued to survive and serve, hosting another innovative program.[94]

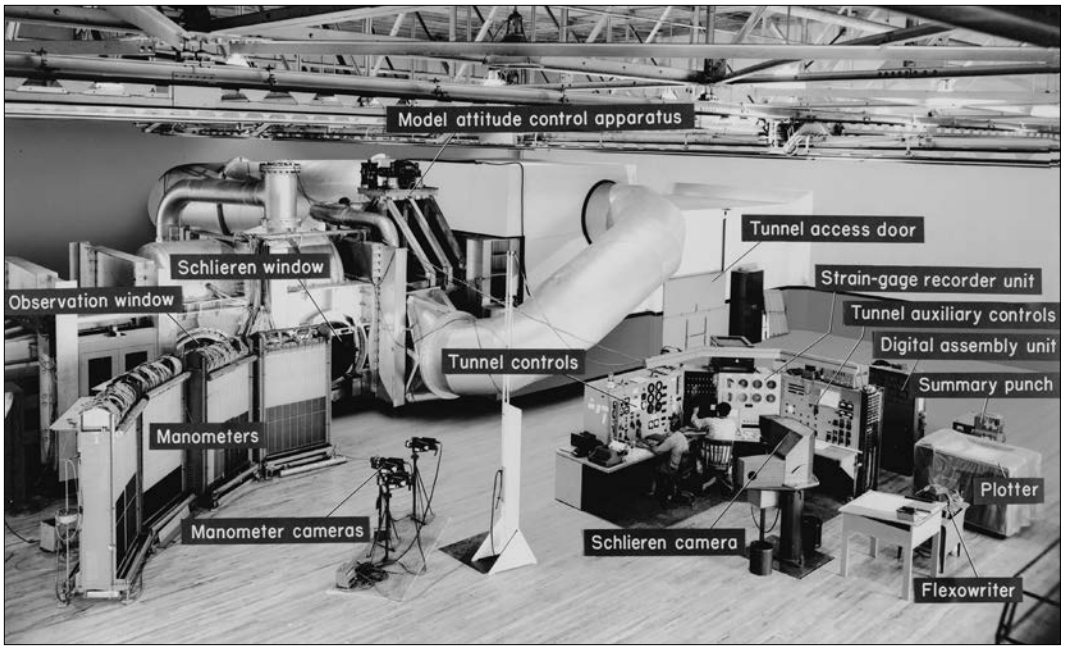


The major components of the 6- by 6-Foot Supersonic Tunnel are identified in this cutaway drawing. (Image credit: NASA A-1300-1)

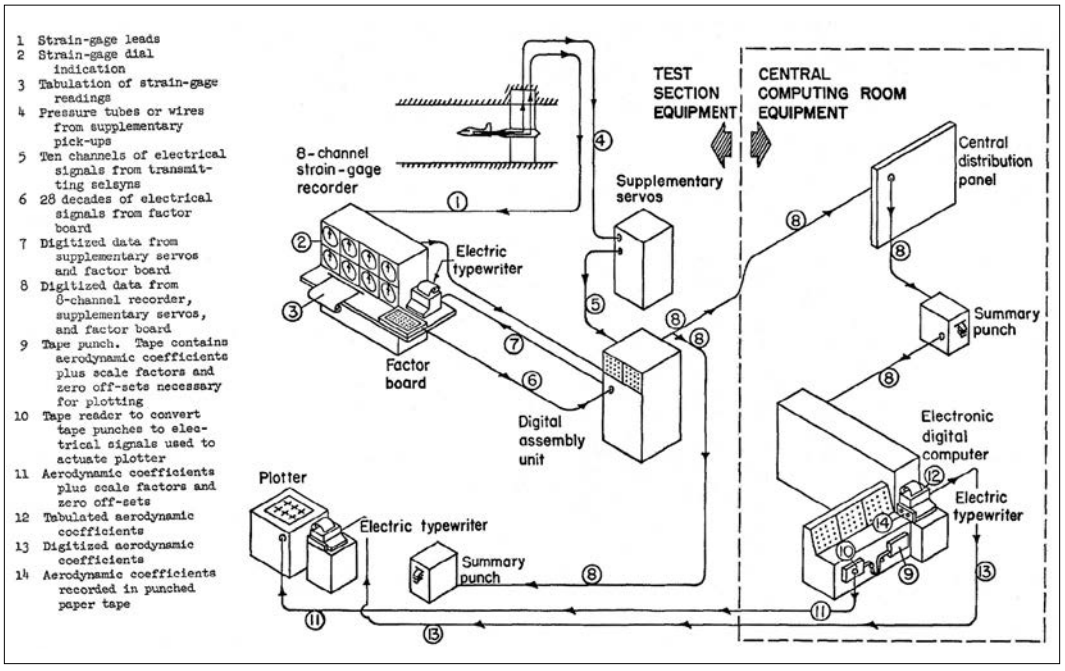
The 8- by 8-inch pilot tunnel's sliding-block nozzle in 1946. The block is shown at the end of its stroke with the smallest vertical throat dimension and highest Mach number. Retracting the block to the right increased the vertical opening and reduced the airspeed in the test section. Note the hand crank and rotation counter used to position the block in this pilot nozzle. This nozzle design was scaled up for the 6- by 6-Foot Supersonic Tunnel. (Photo credit: NASA A-9364)



The rotor of the 6- by 6-Foot Supersonic Tunnel's eight-stage axial compressor is visible with the case opened. Note the stator blades mounted inside the case. These fit between the rows of rotor blades. (Photo credit: NASA A-14376)



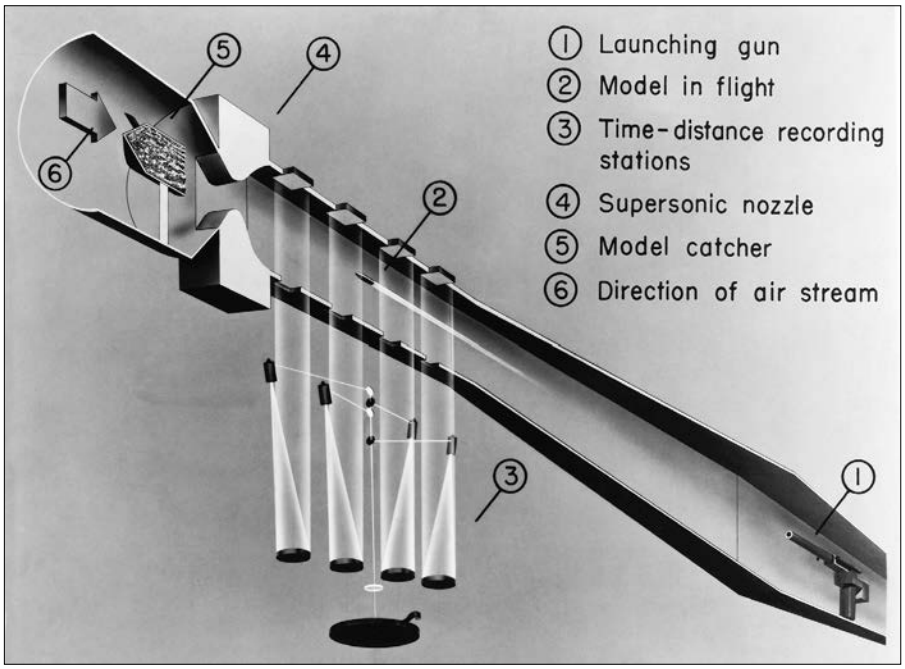
This view of the 6- by 6-Foot Supersonic Tunnel's roomy test chamber identifies the control and data acquisition system components. The tunnel's test section is in the left background, with its flow from left to right. (Photo credit: NASA A-21175)



This diagram shows the equipment and functioning of the automated data acquisition system pioneered in the 6- by 6-Foot Supersonic Tunnel. This system originally monitored eight strain gages. (Image credit: NASA TM-80995, Fig. 3)

A researcher inspecting a model in the 6- by 6-Foot Supersonic Tunnel's test section in 1948. Note the two circular schlieren windows and the fact that the vertical blade supporting the sting does not extend to the floor. (Photo credit: NASA A-13007)

SUPERSONIC FREE-FLIGHT WIND TUNNEL



This 1950 diagram shows the basic functioning of the Supersonic Free-Flight Wind Tunnel, along with its major parts. (Image credit: NASA A-15058)

SIGNIFICANCE

The Supersonic Free-Flight Wind Tunnel (SFFWT) was the first ballistic facility built at Ames and the first known counterflow tunnel in the world. It became the prototype for other counterflow tunnels, and equipment and techniques developed for it saw wide use in these subsequent tunnels.

DESCRIPTION

Though called a wind tunnel, the SFFWT was more accurately a counterflow tunnel because it used a gun to propel a small model airplane or missile into a stream of air moving toward it. Thus, the total test velocity was the sum of the model's speed and the wind speed, which could be as high as 10,000 mph (approximately Mach 18), though most tests were conducted at slower speeds. The basic facility was a blowdown tunnel that used compressed air from the 12-Foot PT as its prime mover and exhausted it to the atmosphere. Interchangeable, two-dimensional nozzles for Mach 2 and Mach 3 were mounted to the settling chamber outlet to produce the desired air speed. The settling chamber contained a central chamber that served to catch models at the end of their flights, so the air flowed through the annular space around it, re-merging just ahead of the nozzle entrance.

The SFFWT originally featured an 18-foot-long test section, 1 by 2 feet in cross section, that was fitted with seven windows, four at 5-foot intervals on the top and three at 7-foot, 6-inch intervals along the side. Each window was fitted with a high-speed camera and spark light to photograph the model as it passed the station, generating shadowgraphs of the model and its shock and turbulence patterns. The test section was later replaced with one 27 feet long and 1.5 by 1.7 feet in cross section, which was divided into nine 3-foot-long shadowgraph stations. Air exited the test section into a diffuser and exhausted to the atmosphere. Two 90-degree bends in the exhaust duct, the first of which included turning vanes, prevented stray light from entering the test section from outside, and the tunnel's interior was painted flat black to minimize reflections.[95]

The models were fired from a variety of powder-charge guns, depending on the model's size and weight, and the desired flight speed. Bore diameters ranged from 0.22 to 3 inches, with the smaller calibers used for bodies of rotation and the larger ones for winged models. All models measured 4 inches long. Winged models and others whose size or shape did not exactly match one of the guns were launched in plastic containers known as sabots. Each sabot consisted of several parts that were carefully machined to fit the model and gun bore snugly. It was mounted on a powder cartridge and loaded into the gun's breach. The selected gun fit in a mount at the end of the diffuser, approximately 17 feet from the test section, and it fired along the tunnel's centerline. The parts of a properly designed and fitted sabot would separate soon after it left the muzzle without imparting an angular disturbance on the model, leaving it to fly a true path. The model catcher in the settling chamber was filled with a relatively soft material that would deform to capture and stop the model after its 40-foot flight, often with minimal or no damage. The trapping material was renewed before each test.

Shadowgraphs were the primary record of each test, and Mach-Zehnder interferometer photographs could be made as needed. Each shadowgraph station included a spark light that produced a flash of about 0.3 microsecond's duration. The light was collimated using spherical mirrors and passed through the test section and onto high-speed photographic film. The model tripped the spark by interrupting the beam of a photoelectric detector at each station. Each photograph recorded part of a scale that extended the length of the test section to yield a distance measurement. Time was recorded using an optical technique that projected a small portion of each spark-light flash on a rotating film drum. Also projected onto this film were precisely controlled sparks from a mercury arc lamp, which was set to flash at 10-, 20-, 50-, or 100-microsecond intervals. These time and distance data allowed the researchers to calculate a variety of aerodynamic parameters.

The SFFWT was unusual in that it was constructed underground in a concrete vault measuring 7 by 7 feet in cross section. Reachable via two stairways, the floor is approximately 8 feet below grade. Except for fittings and penetrations, only the concrete roof of the vault and adjacent concrete sidewalk panels are visible at ground level.

HISTORY

The SFFWT was a unique attempt to solve some of the problems associated with other high-supersonic research facilities during the early years of such research. While still generally considered to be part of the supersonic flight regime in the mid-1940s, wind tunnel testing at speeds above about Mach 5 had revealed that the air would start to liquefy if not heated, causing inaccurate results and model damage. Generating such high speeds also presented issues relating to turbulence and wall boundary layers that tended to worsen with increasing speed.

In 1946, H. Julian "Harvey" Allen, Ames's leading high-speed aerodynamicist, proposed combining a blowdown wind tunnel with a ballistic range. He reasoned that such a device would add the speed of the air in one direction to that of a free-flying model launched into the air stream in the opposite direction to produce a net speed much greater than either alone. With a gun of some sort firing a model at around 10,000 feet per second (6,800 miles per hour), the tunnel would only have to generate air velocities on the order of Mach 2 or 3 to yield test speeds of Mach 9 or greater. While the concept was simple and used mostly known components, executing it required some ingenious thought and great precision regarding measurement techniques, since the duration of the test would be a fraction of a second.[96]

A second advantage to the counterflow tunnel would be a high Reynolds number. For a given size model, the Reynolds number with the air flowing would be approximately three times that in still air. Furthermore, the Reynolds number would actually increase linearly as the model's speed increased, since the air's density, viscosity, and speed of sound at a constant flow rate would not change. In a conventional tunnel, increases in air speed altered these parameters and resulted in the Reynolds number decreasing as speed increased.[97]

Allen received approval to build what became the SFFWT later that year, and he assigned Alvin Seiff, Alfred Boissevain, Thomas Canning, and Carlton James, all engineers and researchers on his staff, to design and build it. The design they developed was a typical blowdown tunnel, except that it employed an unusually long test section. Since the model would fly rapidly through the test section, the engineers divided it into seven zones, or "stations," where high-speed photographic techniques could capture the model's action as it passed. At the speeds under consideration, shadowgraph photography would reveal the model and considerable information about the flow field around it, but timing each of the photos would be crucial. They ultimately developed the system described above, which recorded the model's position and attitude, the surrounding flow fields, and a time base.

The team decided to use the 12-Foot PT as the supply reservoir, a source used by several Ames tunnels over the years. It could deliver air at 6 atmospheres (88 psi) pressure, which was high enough to allow the tunnel to exhaust to the atmosphere instead of into a vacuum tank. With this being the first attempt at marrying two high-energy devices, they conservatively chose to place the new tunnel underground as an

added precaution against collateral damage should any accident somehow have explosive effects. A concrete vault was installed to enclose the SFFWT.

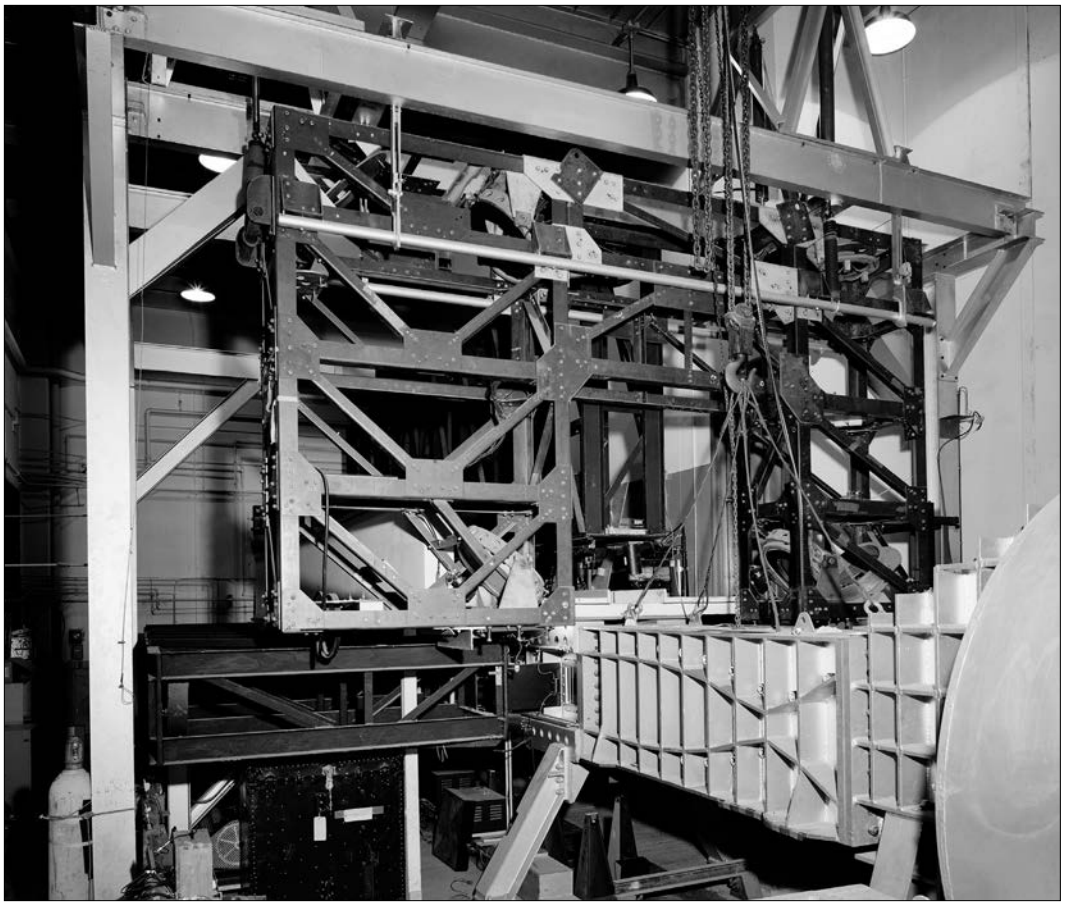
Seiff and his team decided to construct a pair of two-dimensional nozzles to furnish different air speeds, Mach 2 and Mach 3, and they chose a 2- by 1-foot cross section for the test chamber to optimize volume, flow rate, and maximum model size, along with other cost and operating factors. Canning's primary role was to select appropriate launching guns and design the mounting and firing apparatus for them, along with the proper powder charges needed for various types of tests. This role expanded into sabot development to enable the use of non-bullet-shaped models.

The SFFWT opened in 1949 and entered service able to run in three modes, a) a ballistic range with no airflow, b) a counterflow tunnel with Mach 2 airflow, and c) a counterflow tunnel with Mach 3 airflow. Over the years, the Mach 2 counterflow mode saw the most use. A few months were needed to adjust the tunnel, particularly its shadowgraph system, to the point where it operated consistently and produced reliable images. As more complex models were tested, the art of sabot design and manufacture became increasingly complex and precise. Sabots were not new, but the low tolerance for effects on the model during sabot separation raised their level of sophistication considerably.[98]

At the project's initiation, the engineers believed that the shadowgraph system would allow them to compute the model's drag coefficient from the recorded information, but careful observation of the model's image soon allowed researchers to calculate a number of other aerodynamic parameters as well, including lift-curve slope, pitching-moment-curve slope, center of pressure, and roll damping. Over the years, test projects would prompt the development of additional capabilities, such as the determination of static and dynamic stability derivatives, particularly in roll. Some of these tests involved models of the X-15 research airplane.[99]

Two significant modifications improved the tunnel's capabilities during its service life. In operation, it soon became clear that the 18-foot-long test section with seven windows was inadequate to exploit the tunnel's possibilities, and experience with the overlapping top and side shadowgraph stations pointed to an improved design. In 1955, the test section was replaced with one 27 feet long and 1.5 by 1.7 feet in cross section. This test section contained nine distinct, 3-foot-long shadowgraph stations that did not overlap. Coupled with a better shadowgraph technique, improved images recorded longer test flights. The second improvement connected the tunnel to a 9.5-atmosphere (140-pound-per-square-inch) air supply reservoir, which increased Reynolds numbers by 50 percent.[100]

The exact date of closure for SFFWT is not clear, but it is described in a 1965 Ames facilities publication and omitted from one published two years later, implying a closure date between 1965 and 1967. Since that time, large portions of the tunnel have been removed from the vault so that it could be used for storage. While the underground vault and its entrances are intact, little, if anything, of the pioneering counterflow tunnel remains.[101]

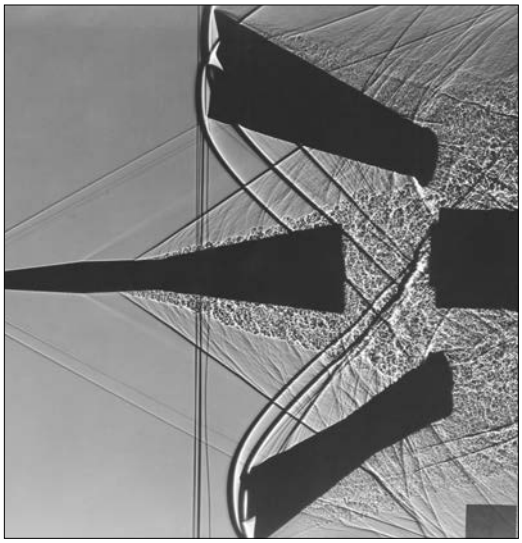


From the 8-foot-diameter settling chamber at right, air flowed through the nozzle and into the Supersonic Free-Flight Wind Tunnel's long test section, largely obscured here by a frame that supported a portion of the tunnel's elaborate optics system (1956). (Photo credit: NASA A-35067)

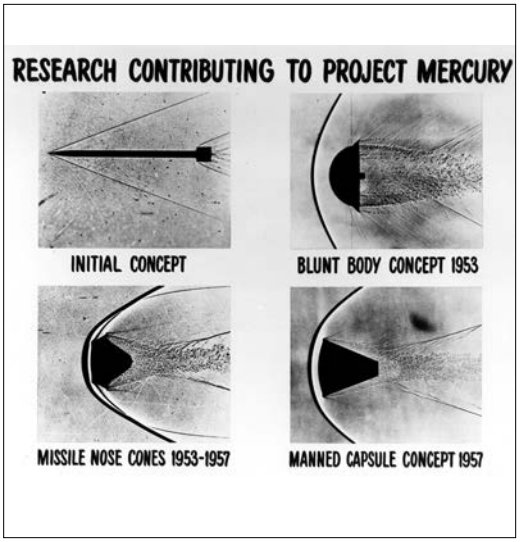
The Supersonic Free-Flight Wind Tunnel test section and control panel. (Photo credit: NASA A-16011)

A technician loads a cartridge with a sabot-enclosed model into the breach of one of the Supersonic Free-Flight Wind Tunnel's launching guns in 1951. (Photo credit: NASA A-15768)

A technician inspects a gun and model in the Supersonic Free-Flight Wind Tunnel in 1951. (Photo credit: NASA A-15769)

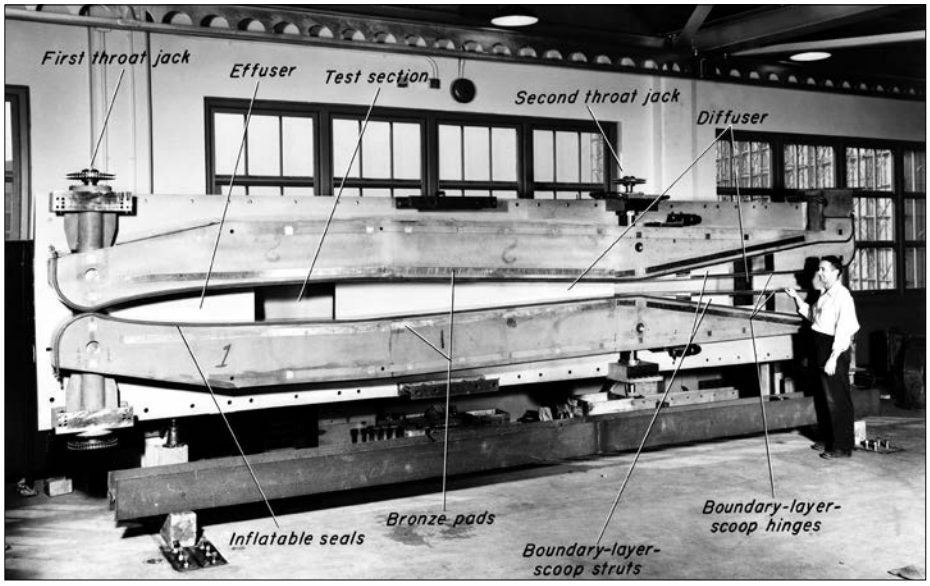


This 1950 shadowgraph shows a three-piece sabot in the process of separating from a model. Separation had to occur smoothly within a few feet of the gun's muzzle. Note the shocks and turbulence. (Photo credit: NASA A-15590)



These NASA shadowgraphs illustrate the various kinds of shock and airflow about different bodies at high Mach numbers. (Photo credit: NASA 60-108)

10- BY 14-INCH HYPERSONIC TUNNEL



This view of the 10- by 14-Inch Hypersonic Tunnel's nozzle and test section block with one side wall removed illustrates the typical proportions for a hypersonic tunnel. The flow is left to right, and the Mach number was adjusted using the two throat jacks to vary. (Photo credit: NASA A-14618.1)

SIGNIFICANCE

The 10- by 14-Inch Hypersonic Tunnel (10- by 14-Inch HYST), also known as the 10- by 14-Inch Supersonic Wind Tunnel, was the first hypersonic (i.e., Mach 5 and above) tunnel built at Ames. Although temperamental to operate, this facility gave engineers and researchers at Ames their first experience with a wind tunnel capable of speeds above Mach 5. The 10- by 14-inch HYST demonstrated that it was possible to vary the speed in a hypersonic tunnel with a variable second minimum in the diffuser downstream from the test section.

DESCRIPTION

The 10- by 14-Inch HYST was a conventional hypersonic wind tunnel[102] that utilized compressed air from the adjacent 12-Foot Pressure Tunnel (12-Foot PT) to achieve test speeds that were variable between Mach 2.7 and 6.3. Inlet air, which had been dried to approximately 0.001 pound of water per pound of dry air when compressed for the 12-Foot PT, was heated by an electric resistance heater as needed to prevent air liquefaction. Heat was generally required for test speeds above Mach 4.4. Below Mach 4.2, the tunnel's main flow exhausted to the atmosphere, but powered evacuation was necessary at higher Mach numbers. Boundary layer extraction scoops at the second minimum removed between 15 and 30 percent of the total airflow, depending

on Mach number. Eight pairs of rotary vacuum pumps with a 30:1 compression ratio maintained this flow.[103]

The tunnel and part of the boundary layer extraction system were located on the second floor of Building N-204-A, along with the tunnel's control panel, a multiple manometer panel for measuring pressures, and a primitive data acquisition system termed an "electronic follow-up system" that recorded the model strain gage data for later analysis.

The tunnel's nozzle throat, effuser, test section second minimum, and diffuser were fabricated as a single unit composed of symmetrical, contoured upper and lower sections and flat sidewalls. Inflatable seals of heat-resistant rubber minimized leakage between the pieces. Boundary layer scoops were included at the second minimum. Both the nozzle throat and the second minimum were adjustable to allow operators to set the test speed and fine-tune the tunnel. At each throat, the adjustments were accomplished by jackscrews turned by a common electric motor through a chain drive. While the two throats were independently adjustable, the nozzle assembly always remained symmetrical. Throat adjustment controls, along with the other tunnel controls, were housed in a free-standing panel adjacent to the test section.

Models were supported on a sting, with force and moment data measured by strain gages incorporated into the sting. These data were magnetically recorded for later analysis. Pressure data were obtained using multi-tube manometer panels that were photographed during test runs. Technicians later read the data from the photographs. A schlieren system and an x-ray densitometer were available to photograph and measure density changes in the flow around the model.[104]

The tunnel's main and boundary layer exhaust flows passed through ducts down to the array of centrifugal evacuators and vacuum pumps that apparently exhausted to the atmosphere. The centrifugal evacuators actually were turbosuperchargers whose drive turbines were turned by excess air from the 12-Foot PT supply compressors. Valves allowed operators to connect the evacuators in a one- or two-stage configuration. Like the vacuum pumps, they exhausted to the atmosphere. The capacities of the 12-Foot PT's compressors and the 10- by 14-Inch HYST's centrifugal evacuators and vacuum pumps allowed the tunnel to run continuously.[105]

HISTORY

Soon after John Becker's success with the 11-Inch Hypersonic Tunnel at Langley in 1945, Ames engineer Alfred J. Eggers, Jr., began looking into ways to improve upon Becker's design. To extend the run time, Eggers decided to use the 12-Foot PT as the tunnel's supply reservoir instead of a dedicated tank and compressor. The 12-Foot PT held some 668 thousand cubic feet of air at 88 psi, and the pressure differential across the tunnel could be raised to approximately 100 psi by exhausting to a vacuum rather than to the atmosphere.

Eggers received approval for his project in 1946, and, assisted by George Nothwang, he began the detailed design. To make use of air discharged from the 12-Foot PT, they located the tunnel in Building N-204-A, which in essence was an addition to the building that housed the drive motor and air handling equipment for the 12-Foot PT. Their calculations soon revealed that, given the capacity of the 12-Foot PT's supply compressors, a 10- by 14-inch tunnel could operate continuously, something rarely achieved with a hypersonic tunnel. By making both the nozzle's throat and the second minimum adjustable, they gave the tunnel a speed range from Mach 2.7 to 6.3. Closing the nozzle increased the speed in the test section, and closing the second minimum downstream from the test section reduced it. But the second throat (or minimum) had a more-important purpose. The strength and location of the so-called normal shock that formed there as the flow decelerated could be altered by careful adjustment of this throat. Such fine-tuning significantly reduced the power losses that usually accompanied the normal shock.[106]

The 10- by 14-Inch HYST entered service in 1950, and, for at least a decade, it was known as the 10- by 14-Inch *Supersonic* Wind Tunnel, since no clear distinction between the supersonic and hypersonic regimes had been established when it opened. In operation, the normal practice was to start the tunnel with the nozzle set for around Mach 3 and the second throat reasonably open. This way, supersonic flow was established easily, but the normal shock formed well downstream in the diffuser. Closing the second minimum moved the normal shock toward the second minimum, thereby reducing its size and strength. Once an optimal setting had been obtained at this low Mach number, the nozzle throat could be closed further to increase the test section Mach number with only small changes to the second minimum needed to maintain a high tunnel efficiency. The process required great care, but, done correctly, it met the designers' goals of variable speed and good efficiency throughout the speed range.[107]

Although a reasonable amount of information about the 10- by 14-Inch HYST's design is known, little about its service life and ultimate disposition has survived. The available literature indicates that the tunnel hosted basic research into hypersonic aerodynamics, particularly the characteristics of conical noses for ballistic missiles.[108]

In the early 1960s, Ames, by then a NASA research center, needed a location for the Vertical Gun Range to support investigations into high-speed impacts in space by objects like micrometeorites. The high-bay portion of Building N-204-A was suitable for it, so management decided to relocate the 10- by 14-Inch HYST to Building N-229, which was close to the center's compressor station. The tunnel and its supporting systems were disassembled, crated, and removed to storage during 1962 and 1963, but the planned reassembly never occurred. The tunnel's components remained in storage for an undetermined period, but they were apparently scrapped at some point. Some of the supporting vacuum pumps may well have found service elsewhere on the center, but no records confirm this. Thus, no portion of the pioneering tunnel is known to survive.[109]

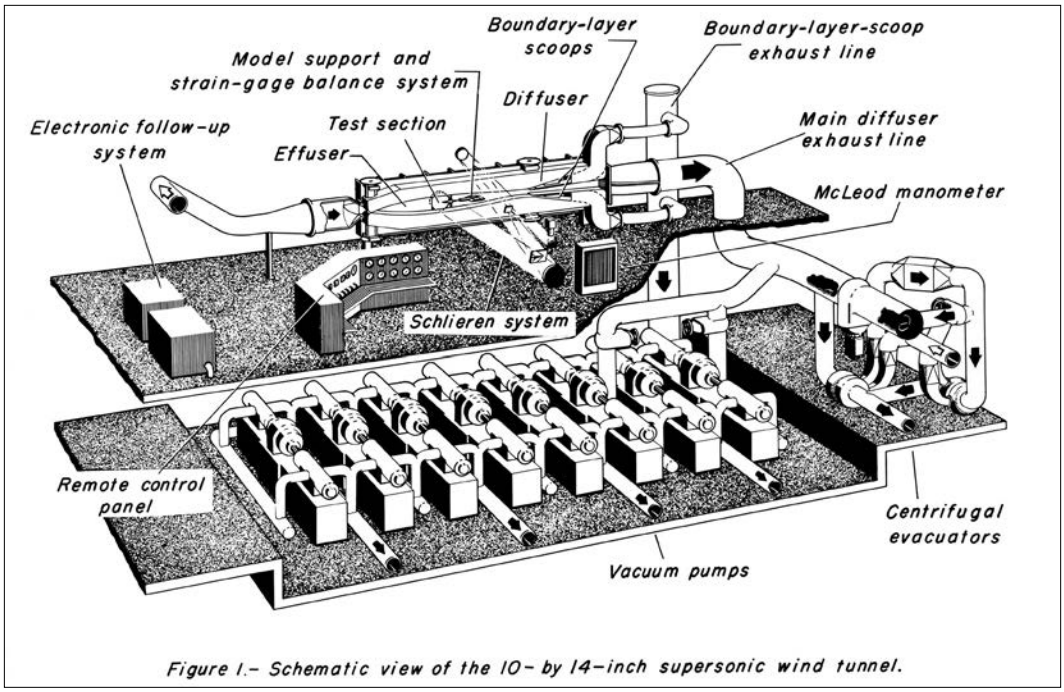
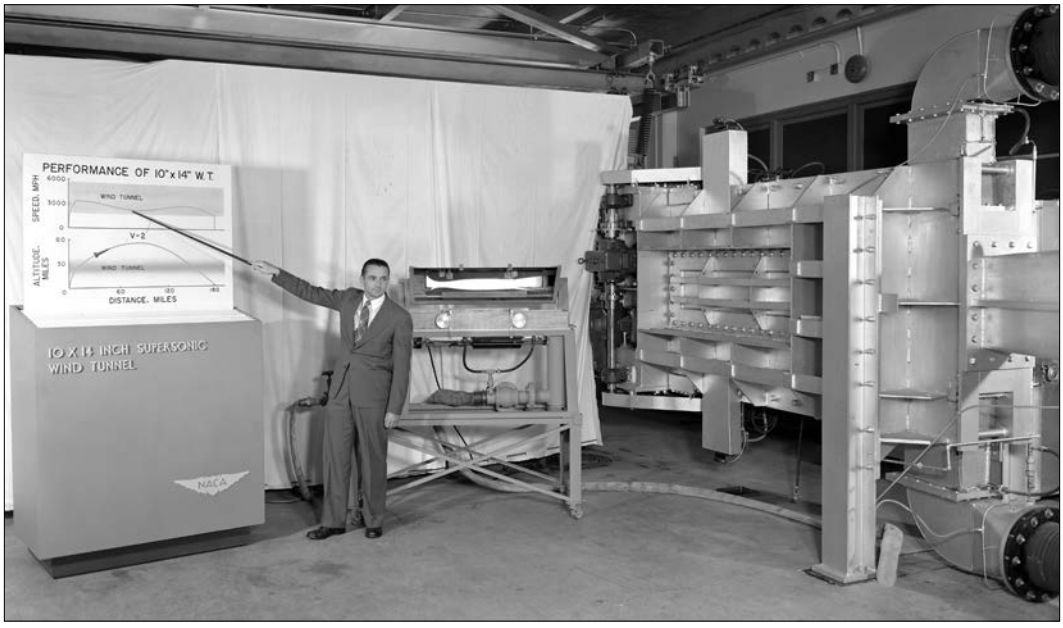


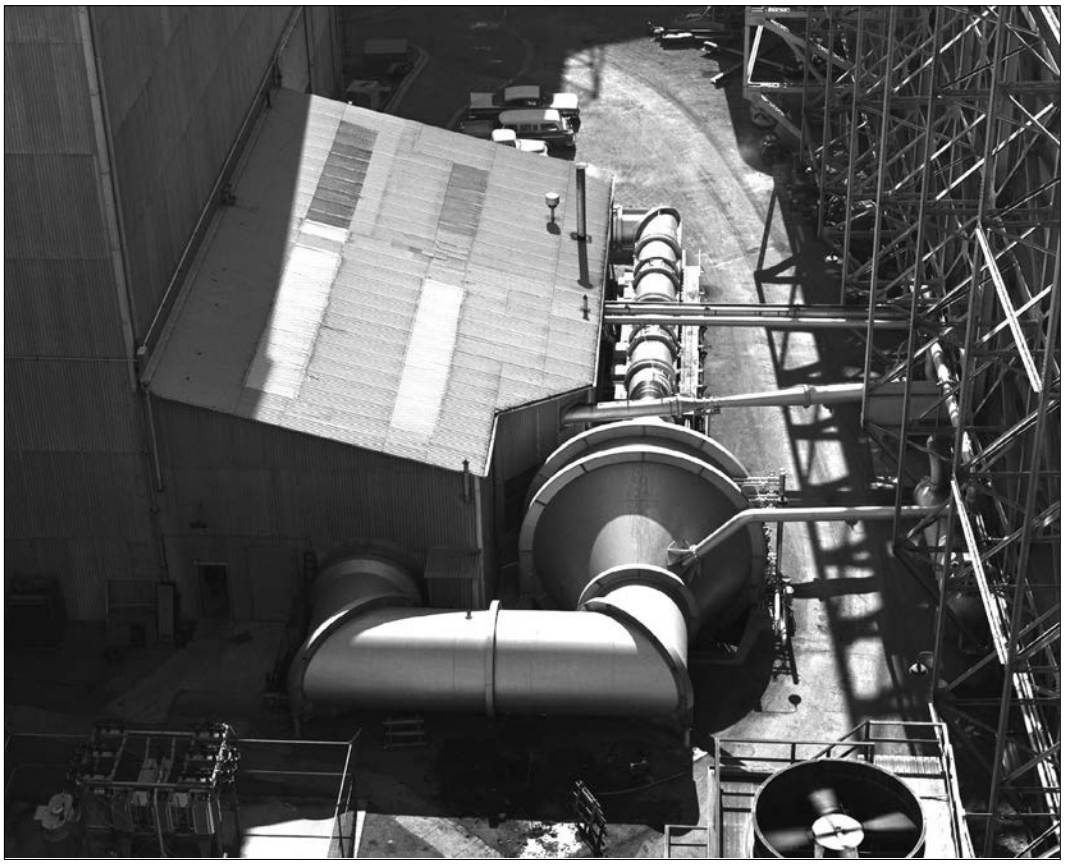
Figure 1.– Schematic view of the 10- by 14-inch supersonic wind tunnel.

This cutaway drawing of the 10- by 14-Inch Hypersonic Tunnel identifies its major components, including the array of vacuum equipment needed. The set of centrifugal evacuators handled most of the tunnel's flow at high Mach numbers, and the vacuum pumps maintained flow at the boundary layer removal slots during test runs. There were some inter-connections for certain situations. The control valve and electric heater for the inlet air are not shown here. (Image credit: NASA A-16487_2)



Demonstrations of the 10- by 14-Inch Hypersonic Tunnel at the 1950 Ames Biennial Inspection. (Photo credit: NASA A-15332)

2- BY 2-FOOT TRANSONIC TUNNEL



The 2- by 2-Foot Transonic Tunnel, as seen from the roof of the National Full-Scale Aerodynamics Complex in 1965. The large cooling section is evident, with the drive section behind it. Note the pipes for air extraction and reintroduction that are routed to compressors located under the NFAC's floor at right. The test section is inside the corrugated metal lean-to structure at left. (Photo credit: NASA A-350705)

SIGNIFICANCE

The 2- by 2-Foot Transonic Tunnel (2- by 2-Foot TT) was the first tunnel designed and built as a transonic tunnel at Ames. It was the first permanent tunnel to utilize a unique design for test section wall slots developed at Ames, and it served as a pilot prototype for the Unitary Plan Wind Tunnel's transonic circuit. The tunnel also was the first one at Ames to utilize color schlieren photography. The 2- by 2-Foot TT was later modified with one of the earliest adaptive-wall test sections at a NASA center.

DESCRIPTION

The 2- by 2-Foot TT was a closed-circuit, single-return, variable-pressure tunnel specifically designed for transonic operation between Mach 0.6 and 1.4. Assigned Building Number N-222, it occupied a portion of the central courtyard of the National Full-Scale Aerodynamic Complex's (NFAC) 40- by 80-foot circuit. The tunnel's nozzle and test

section, as well as the first portion of its diffuser, were housed in a corrugated metal lean-to structure that abuts the NFAC's 40- by 80-foot test chamber, while the remainder of the circuit, including the four 90-degree turns, the aftercooler, and the drive section, were exposed. Overall, the tunnel circuit measured approximately 100 feet by 38 feet, not including the aftercooler bulge. The 2- by 2-Foot TT had a circular cross section, except for the 2- by 2-foot-square test section and its upstream and downstream transitions. The tunnel was constructed of steel plate with external stiffening rings, most of which have integral legs to support the tunnel entirely above the ground. Originally designed for operational static pressures of 0.2–3 atmospheres (3–44 psia), the tunnel was restricted to atmospheric pressure after cracks were discovered in the 1980s. All four corners are mitered and fitted with turning vanes.[110]

The 2- by 2-Foot TT originally incorporated a flexible-wall nozzle. The top and bottom walls varied in thickness longitudinally so that the deflection from a single jack produced a contour ideal for Mach 1.25 and close for other speeds. The leakage problems experienced in the 1- by 3-Foot Supersonic Tunnel's flexible-wall nozzle were eliminated by placing the entire nozzle inside a plenum that served as its pressure vessel.

The original 2- by 2-foot test section used a unique slot design developed at Ames that inserted pieces of corrugated metal in the slots to form long strips of triangular holes. The engineers selected this triangular shape to mimic wing sweepback and, thus, minimize flow disturbances at speeds above Mach 1. Each wall contained 16 of these strips, resulting in a total open area of 6 percent of the total wall area. Ames referred to this design as a "perforated wall." It proved to be a successful design, and it was repeated in the Unitary Plan Wind Tunnel's 11- by 11-foot transonic test section, but the design was not widely adopted elsewhere. The 2- by 2-Foot TT's test section measured 4 feet long. At its exit was what the engineers called an "effuser," which was a stepped entrance to the diffuser. The step had an approximately ⅜-inch gap that opened into the plenum surrounding the test section, and it functioned as the reentrainment channel for plenum air. It was, however, rather inefficient, and the engineers added a centrifugal compressor as a vacuum pump to assist with plenum air extraction. The air it removed was re-injected farther down the diffuser. Models were supported on a sting that had a pitch adjustment of ±8 degrees. By mounting the model with its wings vertical, this became a yaw adjustment. Forces and moments were measured by strain gages mounted in the model.

The original test section was replaced with a slotted, adaptive wall in 1988. The ceiling and the floor were adaptive, while the test section side walls were solid glass that supported two-dimensional airfoil sections. Unlike non-slotted, flexible-wall systems, this system uses controlled air extraction and injection through the test section slots. Based on LDV measurements, it used numerical simulation of the flow field away from the model to predict the ideal, or "free-air," conditions at the wall, and then adjusted the flows through the slots to achieve those conditions. The top and bottom walls are slotted, and the sidewalls were glass to permit laser velocimetry measurements. The upper and

lower plenums were each divided into 16 sections, each having a modulating flow-control valve, to vary the flow through different sections of the slots. Manifolds above and below the test section supplied air through these valves to plenums and slots where air must be injected. The entire device was enclosed within a pressure shell maintained at approximately 2 psi below the tunnel's operating pressure. This served as a vacuum reservoir for those sections where air must be withdrawn, controlled by the same valves, through the slots. A 5,000-cubic-feet-per-minute, 300-horsepower centrifugal compressor drew air from the tunnel's diffuser and delivered it to the manifolds, and a variable-speed axial-flow compressor maintained the vacuum in the test section's pressure shell. Its output was delivered downstream of the aftercooler.[111]

Four 1,000-horsepower induction motors, each turning one rotor of a four-stage axial compressor, generated the tunnel's airflow. The stages were grouped in counter-rotating pairs, and the complete assembly was housed in a long nacelle in the return leg. Motor speed was controlled using a variable-frequency drive.

Downstream of the drive section, the shell expanded to 23 feet in diameter to accommodate cooling coils that removed the compression heat and provided some control over the tunnel's temperature. These coils utilized cooling water supplied from the NFAC system. Downstream from the cooling coils, the diameter reduced to 10 feet, which continued through Corners 3 and 4 to the nozzle entrance.

Positive pressure within the 2- by 2-Foot TT was originally established and maintained by an air compressor that furnished 75-pound-per-square-inch air to a storage tank through a silica-gel adsorption air dryer. Two rotary-type, single-stage vacuum pumps operating in parallel evacuated the tunnel. These were removed during the test section replacement.

HISTORY

Following the 1950 development of the slotted-wall test section that permitted stable transonic wind tunnels, research interest in that regime exploded in all of the NACA laboratories and elsewhere. Consequently, the researchers and engineers submitted a variety of proposals to modify current wind tunnels or build new ones with slotted walls. At Ames, these efforts culminated in the extensive rebuilding of the 16-Foot High-Speed tunnel into the 14-Foot Transonic Tunnel and an 11- by 11-foot transonic circuit in its new Unitary Plan Wind Tunnel complex. While slotted walls clearly worked, the concept was still open to improvement, and engineers at Ames began some development work of their own. They believed they could improve upon Ray Wright's design at Langley, and they wanted the best possible design for their two tunnels.

Where Wright and John Stack at Langley preferred to stay with the simplest possible design, H. Julian "Harvey" Allen at Ames was inclined to pursue a more-complex design that promised smoother performance during the sub-to-supersonic transition. Allen preferred a flexible nozzle to optimize the speed distribution in the test section, and he, along with Joseph Spiegel and Leslie Lawrence, also thought the slot configuration

could be better. To validate their concepts, they sought and received funds to build a 2- by 2-foot pilot tunnel. To minimize its cost, they constructed the 2- by 2-Foot TT in the central courtyard of the 40- by 80-Foot Full-Scale Tunnel (now part of NFAC) and used that tunnel's utilities and services where possible.

The team's analysis of slot performance led them to a "perforated wall" design that featured strips of corrugated metal in the slots. These strips, machined from aluminum, formed a series of triangular holes instead of one continuous slot. The triangular shape was chosen to resemble the leading edge of a sweptback wing and, thus, minimize shock generation from the edges of the holes. All four test section walls were composed of alternating slots and windows for observation and schlieren photography. A plenum surrounded the test section, but conventional reentrainment baffles would not work without open slots, so they added a step to the diffuser entrance with a gap called an "effuser" that permitted the reentrainment of plenum air. After it proved to be inefficient, they installed a surplus centrifugal compressor as a vacuum pump to assist with plenum air extraction. The air it removed was re-injected further down the diffuser.

The 2- by 2-Foot TT opened in 1951, and it validated both the flexible-nozzle and perforated-wall designs, delivering continuously variable Mach numbers from about 0.6 to 1.4 with low Mach number variation across the test section. Additionally, the calibration tests revealed auxiliary suction on the plenum to be a very effective way to increase the tunnel's efficiency. Removing between 1 and 1.5 percent of the total air mass through the test section mass flow reduced the main drive power consumption by as much as 15 percent. This has subsequently been employed in other tunnels to improve efficiency or to raise maximum Mach numbers.[112]

In addition to being a successful pilot for the larger tunnels, the 2- by 2-Foot TT became a valuable research venue in its own right, especially for studies into the basic nature of transonic and low-supersonic flows. Early tests revealed a weakness in the test section design, in that the many glass panels between the slots could not be aligned closely enough in plane to permit conventional black-and-white schlieren photography. Fortunately, a color-schlieren technique could capture the needed density differentials in environments unacceptable to the black-and-white methods, and Ames researchers pioneered the use of this technique in the NACA.[113]

Researchers also used the tunnel to perform tests to determine how well various materials withstood highly turbulent transonic flow. Several of these test programs involved possible replacements for the silica tiles and Nomex blankets covering most of the Space Shuttle orbiters' surfaces. A frame holding a sample of the material replaced one side panel of the test section, exposing its surface to the airstream. If desired, a probe could be inserted to produce a shock wave. This method proved to be an effective, low-cost way to evaluate the durability of numerous materials and to determine the aeroelastic effects of thermal protection system materials on the airframe.[114]

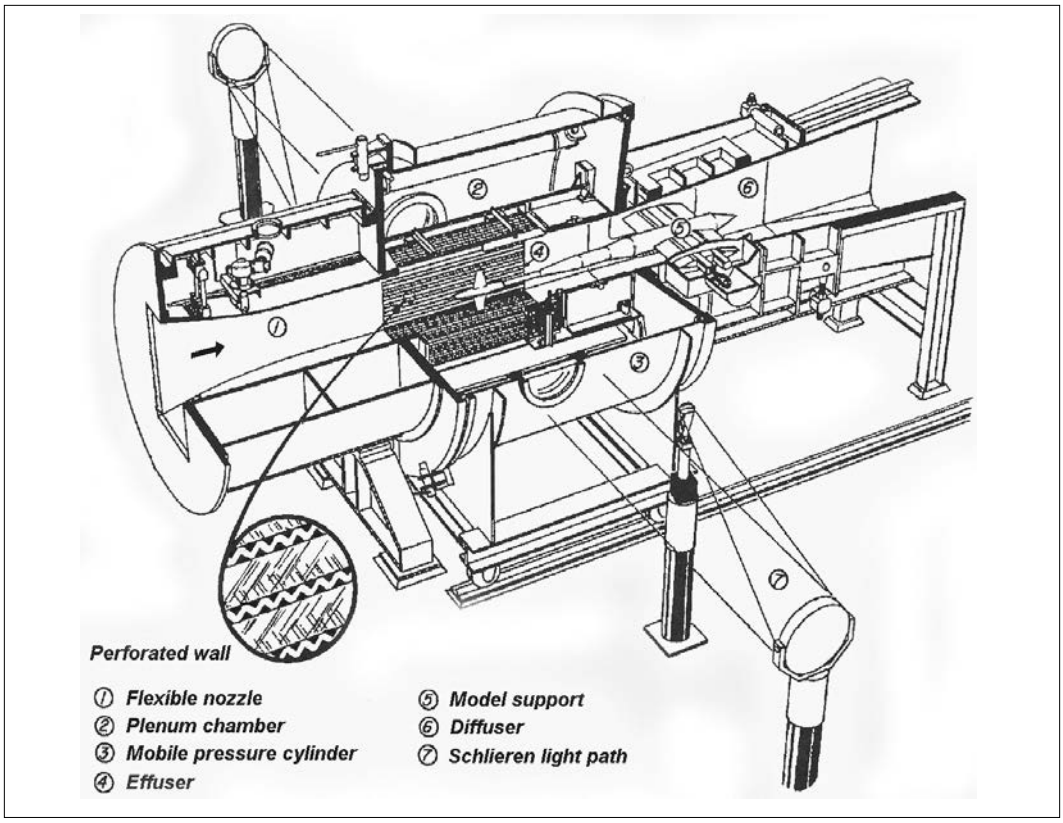
The amount of work done in the 2- by 2-Foot TT began to wane during the 1960s, but Ames maintained the tunnel, and it was available to support some innovative testing

and wind tunnel development work in the late 1970s and 1980s. Aeronautical researchers have been concerned about the effects of wall interference of test accuracy almost as long as they have used wind tunnels, and the addition of compressibility effects and shock reflections at Mach 1 and above only heightened their concerns. With varying degrees of success, numerous physical and numerical techniques were tried to minimize and/or correct for wall interference, but the ideal solution would be to eliminate the walls altogether. While this was not possible, researchers began to wonder if an actively controllable wall, or walls, could create conditions that canceled any negative effects. During the 1980s, the emerging field of computational fluid dynamics (CFD) made the complex analysis of flow fields increasingly practical.

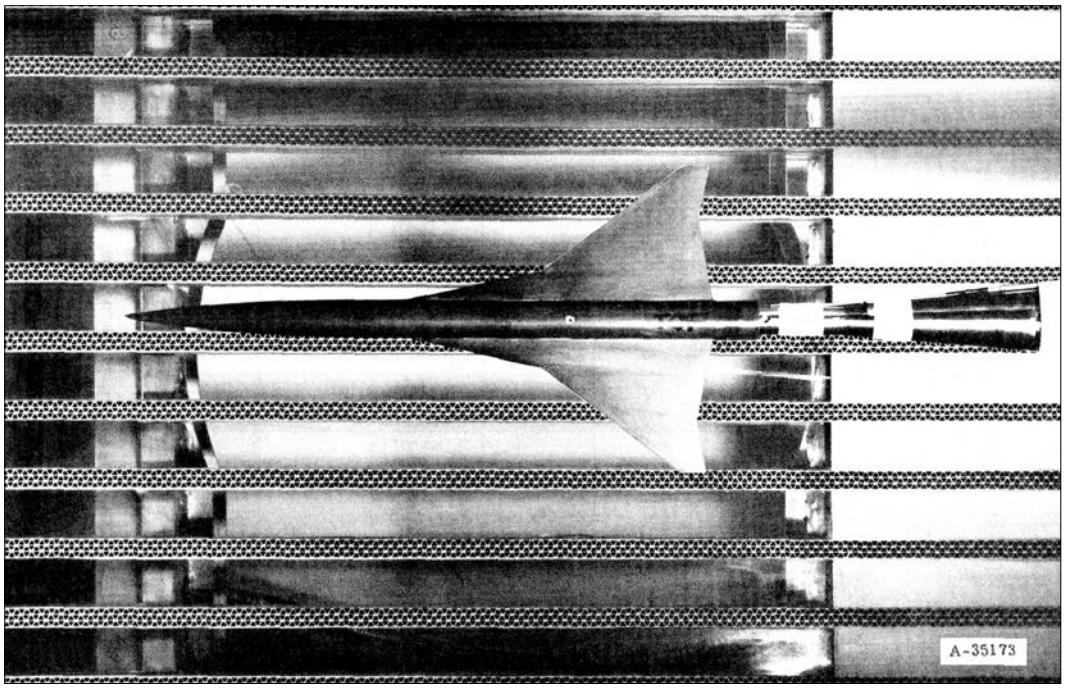
One method already in use with limited effectiveness employed flexible walls that were shaped by actuators into contours that more or less matched the theoretical streamlines at a significant distance from the model. This technique did not, however, work well with slotted walls and speeds above about Mach 0.7. Edward Schairer and Joel Mendoza decided to try an alternate approach. They envisioned a two-dimensional test section with solid sidewalls, but slotted top and bottom. These slots would open not into one large plenum, but rather into many smaller ones that could be individually pressurized or evacuated as needed. With such precise control over many local points, they believed they could use CFD methods to predict the ideal static pressures at these points and then set valves to generate the flow in or out needed to achieve them. The necessary flow measurements near the wall could be obtained using an LDV apparatus.

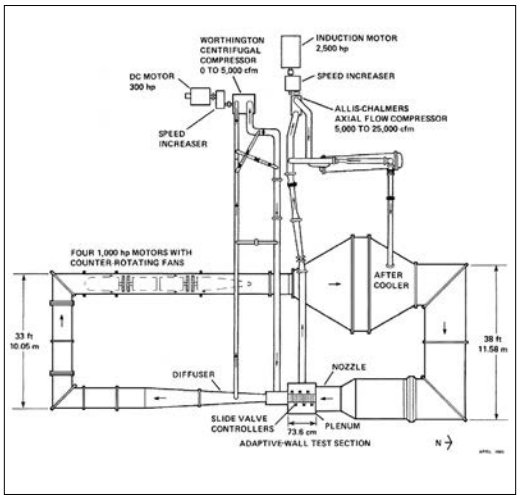
They took several years to develop the basic technique, primarily using an open-circuit, induced-draft 25- by 13-millimeter pilot tunnel, but by 1986, they had developed hardware and software for installation in the 2- by 2-Foot TT. Fabrication and installation took about two years, but an extensive evaluation program verified the approach and pointed to several software revisions that enhanced accuracy.[115]

This project concluded at the time NASA was changing its accounting methods and looking for ways to meet its declining budgets through cost reductions, and the agency decided to close several of its wind tunnels, including the 2- by 2-Foot TT. Thus, the tunnel was mothballed about 1990 and was recently demolished.

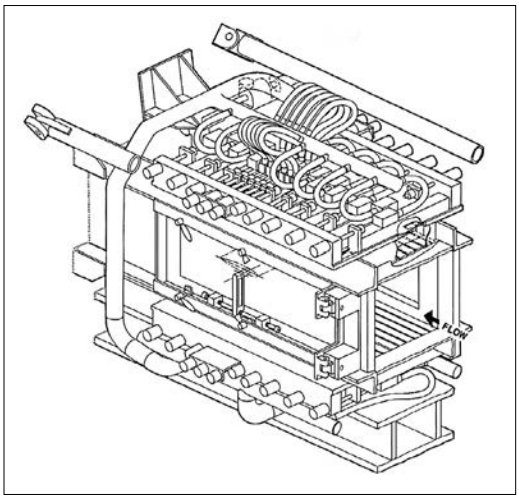


The 2- by 2-Foot Transonic Tunnel's original test section featured slots on all walls and a flexible inlet nozzle. Ames engineers used slots with corrugated spacers in what they termed "perforated walls." The drawing (top) and photograph (bottom) show several of these slots, separated by glass windows. Round windows in the surrounding plenum allowed viewing and schlieren photography. (Image and photo credit: NASA A-35173a and A-35173b)

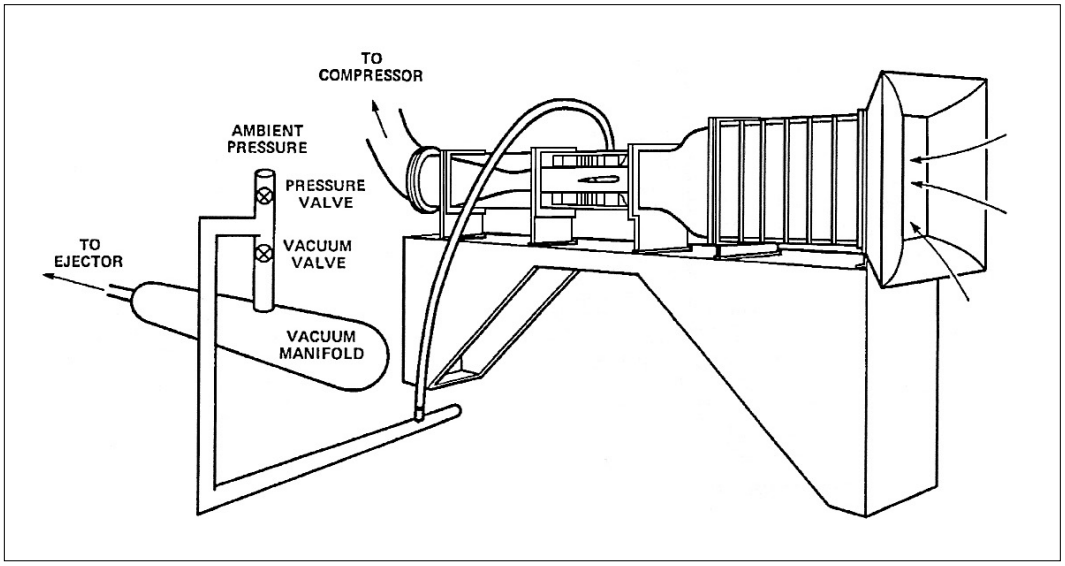




This plan of the 2- by 2-Foot Transonic Tunnel, after the installation of its adaptive-wall test section, identifies the tunnel's major components. Except for the new test section and auxiliary piping changes, the tunnel remained as originally built. The machinery at the top was located beneath the National Full-Scale Aerodynamics Complex's return duct. (Image credit: NASA TM-102207, Fig. 1)

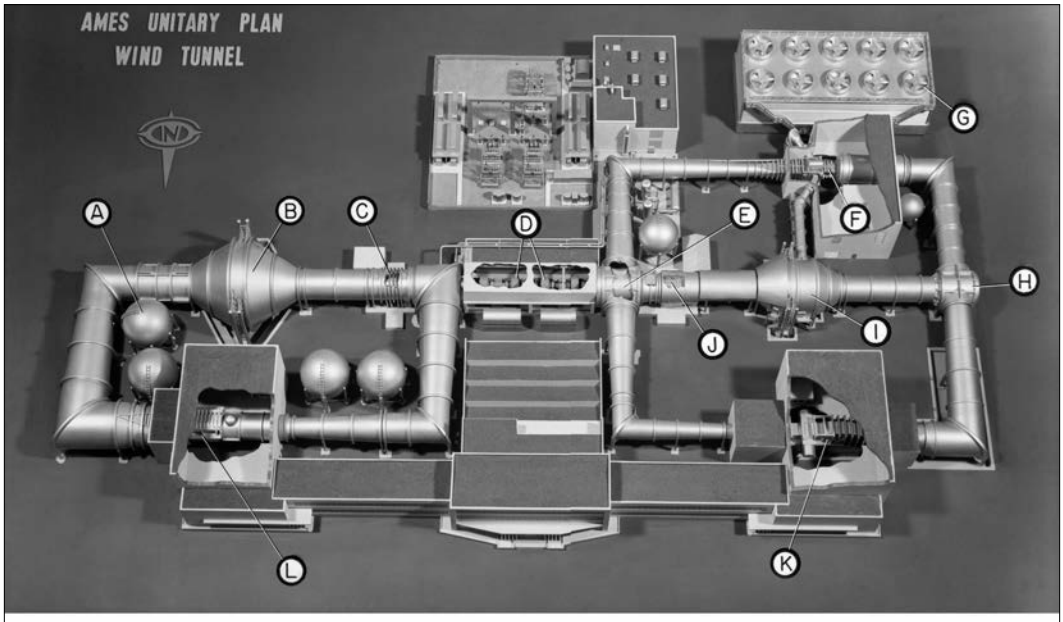


This adaptive-wall test section replaced the original, slotted one in 1988. The complex of valves on top and bottom modulated the static pressure in 32 plenum sections to simulate free-air flow above and below the airfoil model, virtually eliminating wall interference. (Image credit: NASA TM-102207, Fig. 2)



Ames engineers used this 25- by 13-millimeter pilot tunnel to develop the adaptive-wall test section for the 2- by 2-Foot Transonic Tunnel. (Image credit: NASA CR-183152, Fig. 4-1)

UNITARY PLAN WIND TUNNEL



A. Dry Air Storage Spheres
B. Aftercooler
C. 3-Stae Axial Flow Fan
D. Drive Motors
E. Flow Diversion Valve
F. 8- by 7-Foot Supersonic Test Section
G. Cooling Tower
H. Flow Diversion Valve
I. Aftercooler
J. 11-Stage Axial Flow Compressor
K. 9- by 7-Foot Supersonic Test Section
L. 11- by 11-Foot Transonic Test Section

This detailed model of the Unitary Plan Wind Tunnel shows its three circuits and identifies its major components. (Photo credit: NASA A-20393_1-A)

SIGNIFICANCE

The Unitary Plan Wind Tunnel (UPWT) is one of a group of large, high-performance wind tunnels built under a joint, or "unitary," appropriation by Congress to provide supersonic wind tunnels for both military and civilian research and development. As a result of this appropriation, a new supersonic tunnel was built at each NACA laboratory and at a new Air Force development center.

Ames's UPWT was originally intended primarily for transonic and supersonic aircraft research, and it has the widest speed range of the NACA Unitary Plan tunnels. It includes three test sections in separate circuits, driven by a common set of motors. Their speed ranges are complementary, so the UPWT can generate continuously variable test speeds between Mach 0.2 and 3.5. This tunnel has tested most American missiles, supersonic aircraft, and spacecraft built since 1955.

DESCRIPTION

The UPWT is essentially a group of three wind tunnels in one complex that uses a common set of four drive motors. Its eastern section is a transonic circuit powered by

a three-stage, axial-flow compressor and possesses an aftercooler located downstream of the three-stage compressor. Its western portion contains two supersonic circuits that share an 11-stage, axial-flow compressor; a water-bathed section immediately downstream of the compressor; and an aftercooler. Two diversion valves measuring 20 and 24 feet in diameter route air from this common section to one of the two supersonic circuits and back to the compressor. The four drive motors are mounted in tandem on a common shaft between the eastern and western sections, in line with the two compressors, and each end is equipped with a splined coupling that can be connected to or disconnected from its respective compressor. Each of the four wound-rotor induction motors originally generated 45,000 continuous horsepower, for a total of 180,000 horsepower, though they can produce up to 216,000 horsepower for short periods. The motors were rewound in the late 1990s and, when connected in tandem, are rated to deliver 260,000 horsepower continuously.[116] When built, these motors were the largest of their type. They are controlled with a slip-regulator speed control system, and two of the motors are used as a dynamic brake to stop the system from around 700 revolutions per minute in approximately 5 minutes. Only one compressor and one tunnel circuit may operate at a time, but model setup and calibration functions can occur simultaneously in the other two test sections without interference.[117]

Except for transitions surrounding the test sections, the circuits have circular cross sections. Designed for operation between 0.1 and 2.0 atmospheres (1.5 and 29.4 psia), the tunnel was constructed of steel plate with thickness between 0.5 and 2.5 inches stiffened with circumferential stiffening rings. Some of these rings bear on steel legs that rest on concrete footings. A common concrete foundation supports the compressors and motors, while others form the base of the test sections, and expansion joints at key locations in the shell accommodate thermal expansions and contractions. All turns are mitered corners with turning vanes. As with most modern wind tunnels, the diameter of each circuit gradually increases from its test section exit to its settling chamber just upstream of its nozzle. The common supersonic leg and the return leg of the transonic circuit each feature an enlarged section that houses an aftercooler to remove compression heat.

A common two- and three-story concrete office building extends along the UPWT's north side. It houses offices for the complex in its central portion and test section enclosures for the 11- by 11-Foot Transonic Wind Tunnel and 9- by 7-foot supersonic circuits at its ends. Major additions have been built at its eastern end and central area over the years. Separate structures house the 8- by 7-foot supersonic test section and the drive motors. Compressors in conjunction with the large-volume, high-pressure air bottle farm supply flow to each test leg for driving turbine-powered simulators as well as into the makeup air piping, which can be used to improve the rate at which the test leg being used can be dried out before testing begins.[118]

In addition, a separate building houses the makeup air compressor, vacuum pumps, and air dryer. The complex also possesses its own electrical substation and cooling

towers. The 15,000-horsepower Clark centrifugal compressor, with inter- and aftercoolers, through a multistage dryer provides 50,000 standard cubic feet per minute and drives the dry makeup air. The dryer cools the air, using both chilled water and direct-expansion refrigeration coils, and then passes it through a desiccant bed to produce a moisture content of 0.00005 pounds of water per pound of dry air. Dry air is stored at 140 psi in four spherical tanks. A six-cell cooling tower serves the makeup air compressor, dryer, and circuit coolers. Designated Building N-227, the entire UPWT occupies approximately 11 acres of land.[119] A second source of dry makeup air (or vacuum) has been added to the Unitary wind tunnels via an underground tie line from the 12-foot wind tunnel auxiliaries building to the Unitary makeup piping.[120]

While similar in general construction and outward appearance, each of the three circuits is unique in several ways that suit its speed range. The 11- by 11-foot transonic test section (Building N-227-A) is 22 feet long, and it utilizes the slotted wall design pioneered by Ames engineers in the 2- by 2-Foot Transonic Wind Tunnel. Each slot includes a baffle plate in the slot. The engineers selected this triangular shape to mimic wing sweepback and, thus, minimize flow disturbances at speeds above Mach 1. Each wall contains 12 of these strips, and glass panels between the sidewall slots provide an approximately 4- by 10-foot window for observation and imaging. The rear sting model supports used in all three of the UPWT test sections are unique in that they give both 15-degree pitch and 15-degree yaw capabilities to the rear strut model supports via a knuckle-sleeve arrangement. A plenum surrounds the test section, and it has a hatch on top that retracts to open a 10- by 22-foot access portal for model installation, which is handled by a 5-ton overhead crane. The plenum sidewalls have optically clear windows for schlieren photography. The aftercooler for this section, located downstream from the compressor, is 70 feet in diameter.

Test speeds in the transonic circuit are controlled by varying the speed of the three-stage axial compressor and the compressor inlet guide vanes. In addition, supersonic test section flow is achieved by also adjusting the nozzle's sidewalls. This nozzle is a symmetrical, converging-diverging design with multiple jack screws on each flexible wall. The thickness of these walls varies along their length to induce the proper curvature as they are jacked. The top and bottom surfaces are fixed. Speed is continuously variable from Mach 0.2 to 1.45,[121] and most models are supported by a sting that can vary pitch and yaw ±15 degrees.[122]

The 9- by 7-foot supersonic circuit (Building N-227-B) employs an asymmetrical, sliding-block nozzle similar to the one developed at Ames for the 6- by 6-Foot Supersonic Tunnel and also used in the Langley Unitary Plan Wind Tunnel. An electrically driven lag screw translates the contoured lower block to vary the gap between it and a fixed, contoured upper surface. This action simultaneously lengthens the effuser between the throat and test section as speed increases. With fixed sidewalls, this is a two-dimensional nozzle, and it is continuously variable between Mach 1.5 and 2.6. Air in this circuit is propelled by the 11-stage axial flow compressor and cooled by a 45-foot-diameter aftercooler.[123]

NASA generally specifies the sizes of its tunnels' test sections as "height by width." While this test section measures 7 feet high and 9 feet wide, it actually does conform to the convention since the A plane is "on its side" in the horizontal direction.[124] Its useful length varies with Mach number, but the model's center is located within a 5-foot, 6-inch region. Models in the 9- by 7-foot test section are typically supported by a sting that can vary pitch and yaw ±15 degrees. Each sidewall contains two 2-foot, 4-inch-diameter optically clear windows for schlieren photography. Each of these windows is eccentrically mounted in a circular disk such that rotation of the disk can position the window anywhere within a 4-foot, 2.75-inch-diameter circle. In addition, several small porthole-size windows have been added to both the sidewalls and the ceiling of the test section to enable the concurrent use of advanced optical techniques. Matching large windows have also been installed in the plenum pressure vessel sidewalls to significantly improve the size of the unobstructed area that can be covered with the upgraded, large-aperture Schlieren systems. A door has been installed on each side of the test section to improve the access to the test section plenum where advanced optical instrumentation is now installed. Model access is through a 6- by 9-foot hatch in the ceiling serviced by a five-ton overhead crane. The ceiling of the test section is hinged so test articles can be lowered by crane directly into the test section.[125]

The 8- by 7-foot supersonic circuit (Building N-227-C) is the UPWT's fastest circuit. It employs a symmetrical, flexible-wall nozzle with 10 jack screws per side to produce continuously variable speeds from Mach 2.4 to 3.5. Its top and bottom surfaces are flat. This circuit also uses the 11-stage compressor and 45-foot-diameter aftercooler located in the leg shared with the 9- by 7-foot circuit.

The size designation for this test section is opposite that of the 9- by 7-foot circuit, making this test section 8 feet high and 7 feet wide. Its useful length varies with Mach number, but the model's center is located within a 5-foot, 6-inch region. Except for size and access, this test section is similar to the 9- by 7-foot one. Models are typically supported by a sting that can vary pitch and yaw ±15 degrees, and each sidewall contains two 2-foot, 4-inch-diameter optically clear windows eccentrically mounted in a circular disk such that rotation of the disk can position the window anywhere within a 4-foot, 2.75-inch-diameter circle. Model access is through either of two 9-foot, 6-inch-wide by 7-foot, 11-inch-high doors in the test section walls. Although the one on the north side is most often used, both doors are power-actuated, and a 3-ton overhead crane can service either door. Since this circuit has a different mass flow rate than its 9- by 7-foot counterpart, a duct between the test section exit and the aftercooler allows some of the air to bypass the test section and compressor, thereby maintaining the correct test section flow and reducing the pressure differential across the compressor. There is a similar, but much smaller, bypass duct for the 9- by 7-foot.[126]

Each circuit has its own control room, and each test section originally used an automated data acquisition system for up to 10 channels of strain gage signals. This system was based heavily on the one developed for the 6- by 6-Foot Supersonic Tunnel. Three

64-tube manometer panels were available for pressure measurements. Following several upgrades to the Ames data acquisition system and UPWT instrumentation, all test data are now captured automatically, with much of them processed for real-time display. The data system has expanded extensively, now supporting multiple six-component balances, 48 channels of strain gage measurements, 2,048 static pressures, various temperature measurements, and dynamic data acquisition. The control system can direct the tunnel through a preprogrammed test sequence to maximize tunnel efficiency and data consistency between runs.[127]

HISTORY

After the end of World War II, the American aeronautics community, including researchers, manufacturers, and the armed services, realized that the new technologies of jet propulsion, swept wings, and rocket-powered missiles were opening the door to unprecedented advances in aircraft performance. As early as April 1945, researchers at NACA laboratories had begun recommending that the agency build new supersonic tunnels to enable the needed research. The concurrent rise of the Cold War made it imperative for the United States to invest in first-class research facilities that would enable it to master supersonic flight, particularly after the rocket-powered XS-1 proved that such flight was not only theoretically possible, but actually achievable under a pilot's control. A joint NACA-Air Force project, the XS-1's pioneering flight on 14 October 1947, came less than a month after the U.S. Air Force was created as a separate service, and powerful generals of the new service pressed hard for any development that would advance its capabilities and influence. Not wanting to be outdone, the Navy's Bureau of Aeronautics also established a joint project with the NACA that produced the D-558-1, a jet-powered research plane capable of Mach 0.99.

In-flight data from these research airplanes showed some significant discrepancies from wind tunnel tests run during their design, most seriously in the transonic and supersonic speed ranges. These data reinforced the belief of many researchers that new, advanced wind tunnels were essential if these flight regimes were to be exploited. Engineers in the NACA, Navy, and Air Force had confidence that large supersonic tunnels could be built, and each organization developed plans for a new supersonic research center, but they were well aware that the cost and power requirements would be enormous. Ultimately realizing that Congress would not fund separate massive construction projects for each, the NACA and the armed services took the unprecedented step of proposing "...a unitary program to provide for the coordinated responsibilities of the Army, Navy, CAA [Civil Aeronautics Administration; the precursor to the Federal Aviation Administration], and NACA...."[128]

After considerable debate and revision, Congress passed the National Unitary Wind Tunnel Act of 1949, authorizing $136 million for three NACA tunnels, one at each of its laboratories. The act also authorized $100 million for the Air Force to build a new development center at Tullahoma, Tennessee, and $10 million for certain university tunnels. The

NACA's funding was for an engine research tunnel at the Lewis Laboratory in Cleveland, Ohio; a tunnel for missile research at the Langley Laboratory in Hampton, Virginia; and an aeronautical tunnel with transonic and supersonic capabilities at Ames.[129]

Design work on the UPWT began in late 1949, before Congress had released any of the appropriated funds to the NACA. The entire project for all three laboratories was coordinated in Washington, with former Ames project manager John Parsons in charge. Parsons appointed Ralph H. Huntsberger to direct the Ames effort, and he picked some of Ames's best engineers, including Adrien Anderson, Norman Martin, and Paul Radich, to tackle various aspects of the project.

The original concept for the UPWT had only one circuit with an 8- by 8-foot test section supposedly capable of operating between Mach 0.7 and 3.5, but it soon became clear that the transonic and supersonic ranges required separate test sections with different designs. Even then, the projected cost of a single 8- by 8-foot supersonic circuit capable of Mach 1.4–3.5 was too expensive for the budget to bear. By making careful cost comparisons between various size, speed, power, and cost trade-offs, the team finally developed the three-tunnel set that makes up the UPWT. With some fairly minor cross sectional changes, they could obtain overlapping speed ranges in the three circuits and, thus, meet the overall Mach 0.7–3.5 requirement. To help contain costs, a common set of motors could power any of the tunnels, albeit one at a time. Further investigation revealed that the two supersonic circuits could be conjoined to utilize a common compressor and aftercooler. With the design complete, contracts were let for the major components, and construction began in 1951.[130]

Following a construction period of about four years, the complicated UPWT first ran in 1955, and after checkout and calibration, it was declared operational the following year. The UPWT had cost approximately $32 million to build, but bookings for test programs soon filled its schedule and began to justify the investment. As anticipated, most of its test programs have involved aircraft aerodynamics, and most of American's commercial, military, and research aircraft have been tested in at least one of the UPWT's three circuits. Research projects such as NASA's Supersonic Commercial Air Transport (SCAT) design found their way into the schedule as well, as have test programs for all crewed American spacecraft. Some vehicles, such as the Space Shuttle, were tested in all three of the UPWT's circuits.[131]

The UPWT has been improved through several modification programs since 1956, but the tunnel's heavy usage continually delayed any major rehabilitation and modernization projects that would involve extended downtime. By 1988, three decades of heavy service had taken their toll on the tunnel's structural, mechanical, and electrical systems, and researchers also wanted to install a number of important innovations that had come about since 1956. Engineers at Ames began to develop a modernization plan, which rose in priority between 1989 and 1992, as a center-wide inspection and recertification program for pressure vessels found over 9,500 feet (27 percent) of defective welds in the UPWT's shell. By 1994, the engineers had combined these vital repair needs with

a wide variety of other modernization and rehabilitation needs into a comprehensive project estimated to cost approximately $80 million. With the high usage and essential capabilities of the UPWT serving as justification, the funds were approved.[132]

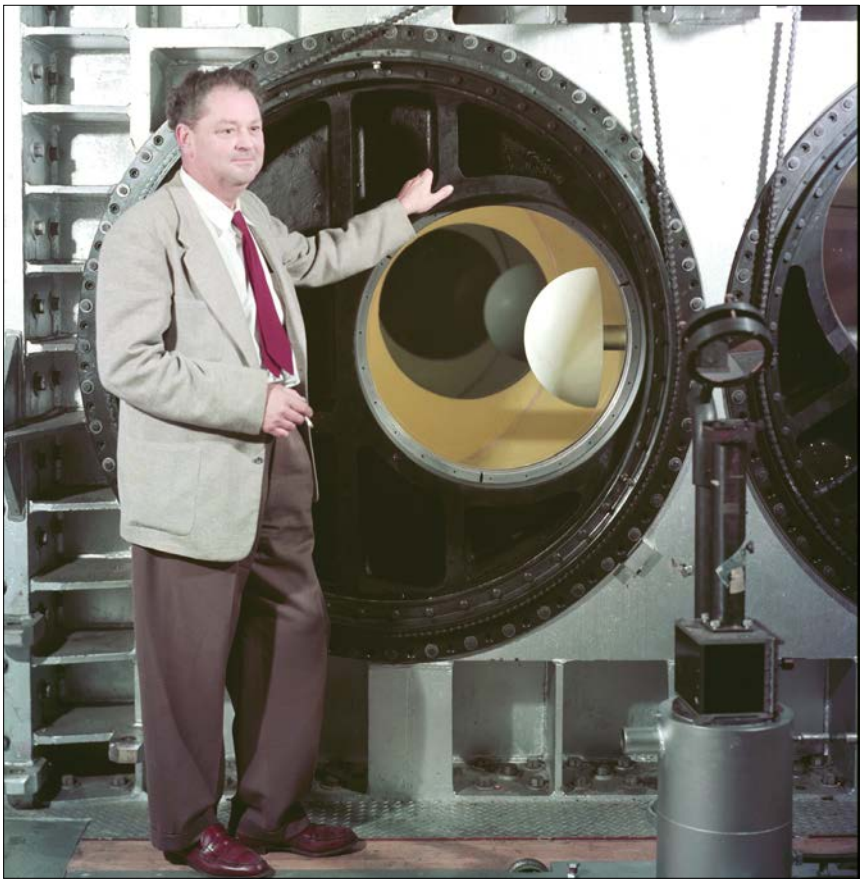
The extensive amount of work was accomplished between 1993—some funds were available before 1994—and 1999. It was done in several stages, with 21 specific projects done by multiple contractors under Ames's management. The supersonic circuits required the least work, so they were scheduled first, with the 8- by 7-foot circuit modernized during 1993 and 1994, and the 9- by 7-foot circuit following in 1994–95. These circuits required weld repairs, but the primary changes were the installation of new control rooms and the complete replacement of their original instrumentation and control systems. The third phase involved a rewelding of all three UPWT circuits, the UPWT's main drive motors, the makeup air compressor, the electrical power system, and most other auxiliary systems.[133] As in the supersonic circuits, the transonic circuit and the auxiliary facility received new control rooms, along with entirely new instrumentation and control systems. Several modifications to the transonic circuit substantially improved its flow quality and reliability. One of the objectives had been to automate the tunnel's operation so that preprogrammed test sequences could be run. This was accomplished by a new distributed control system and new motor control equipment. Rewinding the drive motors allowed the tunnel's total continuous power to increase to 260,000 horsepower.[134]

While UPWT bookings remained strong into the 1990s, utilization of the 8- by 7-foot circuit all but disappeared, thanks to changing public priorities, significant changes in the aircraft manufacturing business, and few new high-performance airplane and spacecraft projects. During this decade, NASA instituted a "full cost accounting" policy that essentially priced most of NASA's specialized tunnels out of the commercial market, and the centers had no choice but to begin closing tunnels that could not economically support themselves. With no time booked, the 8- by 7-foot circuit did not reopen at the completion of the modernization project in 1997, and it remains closed, though intact. The 11- by 11-foot transonic and 9- by 7-foot supersonic circuits still enjoy a healthy booking level of both NASA and outside test programs, and they do not appear to face imminent closure.

The UPWT has been recognized both for its contributions to the nation's aerospace programs and for its engineering excellence. To recognize its vital role in the development of American aircraft and spacecraft, the National Park Service designated it a National Historic Landmark on 3 October 1985. The American Society of Mechanical Engineers recognized the UPWT's unique design and the advances in engineering needed to successfully build it and designated it an International Historic Mechanical Engineering Landmark on 10 May 1996. Bronze plaques commemorating these designations are displayed in a small plaza near one of the UPWT's large diversion valves.[135]

Construction of the Unitary Plan Wind Tunnel's three-stage compressor in 1958. The three-stage axial compressor generates the transonic circuit's airflow, and an 11-stage axial compressor serves both supersonic circuits. Only one circuit and compressor can operate at a time, so one of the two splined couplings connecting these motors to the compressors must be disengaged. (Photo credit: NASA A-24046)

These two aerial photographs show the Unitary Plan Wind Tunnel in 1966 (top) and as it appeared about 1990 (bottom). While new buildings have been added to the complex, the tunnel, though modernized, is essentially unchanged. The 8- by 7-foot circuit, next to the cooling tower, has been closed since 1993. (Photo credits: NASA AC-38286-2 and NASA AC74-1400)



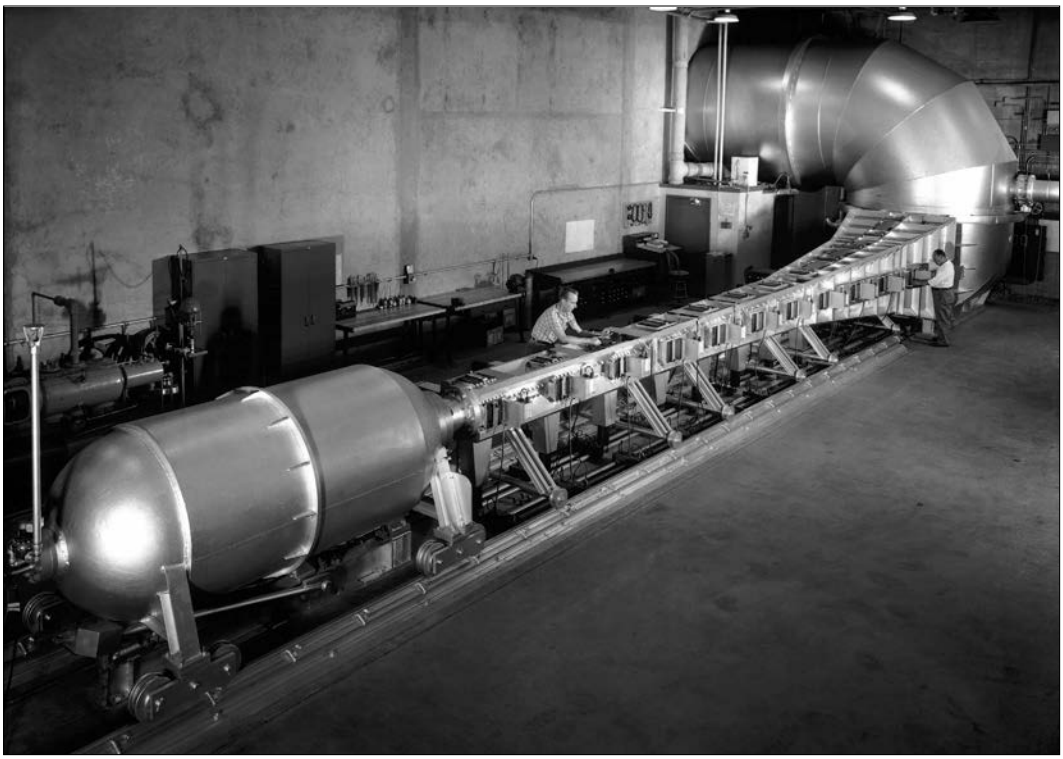
Harvey Allen by the 8- by 7-foot test section with one of his blunt reentry designs installed for testing in 1957. (Photo credit: NASA A-23438)

This attractive plaza that displays the UPWT's many awards is seen here 1999 in the shadow of one of its two diversion valves. (Photo credit: NASA AC99-0101-3)

A researcher checking an Orion crew escape system model in 2008 prior to tests in the 9- by 7-foot test section. (Photo credit: NASA ACD08-0255-008)

Test of the Common Research Model T11-0216 in the Ames 11-by-11-Foot Unitary Plan Wind Tunnel in 2010. (Photo credit: NASA ACD10-0063-004)

ATMOSPHERIC ENTRY SIMULATOR



This 1959 view of the Atmospheric Entry Simulator shows everything except its light-gas gun, which was located behind the exhaust duct elbow and far wall. Visible from left to right are the air reservoir, test section, and exhaust duct. The test section was fitted with 12 shadowgraph stations. Note that most components are mounted on rails to allow easy access. (Photo credit: NASA A-24013)

SIGNIFICANCE

The Atmospheric Entry Simulator (AES) was the first NASA facility built to investigate the reentry of ballistic missile warheads into Earth's atmosphere, and it was the first to produce a varying density atmosphere through its test section.

DESCRIPTION

The AES was a specialized counterflow tunnel with a hypervelocity gun that launched models into an air stream moving in the opposite direction at a supersonic speed. It consisted of a compressed-air reservoir, 4 feet in diameter by 8 feet long; a 40-foot-long test section divided into 12 sections for shadowgraph stations; a large exhaust duct to a 32-foot-diameter vacuum sphere; and a two-stage light-gas gun that launched models into the test section. It was erected in Building N-224, an addition to N-223, which housed the Hypervelocity Ballistic Range used for impact studies.[136]

The tunnel's unique feature was the geometry of its test section. Square in cross section, its height and width increased from 1 to 6 feet exponentially along its length. With a uniform airflow through the test section, this geometry generated a continuous

reduction in the air's density that simulated a 130,000-foot range of altitude. Each of the 12 divisions contained an orthogonal shadowgraph apparatus that was triggered by a photocell as the model passed through it. The photocell signals also tripped electronic counters that collectively provided a time-distance record of the flight.

Models were launched at speeds of approximately 20,000 feet per second (13,600 miles per hour) by a two-stage light-gas gun. The two-stage design boosted the power of a single-stage gun by the addition of a second light-gas chamber between the first one and the barrel. In the AES's gun, igniting the powder charge produced a strong shock that traveled down the 4-inch bore, compressing and heating the helium it contained. This energy ruptured a diaphragm and accelerated a lightweight piston down the second, 2.25–inch bore at a supersonic speed, thereby compressing and heating this second charge of helium to about 100,000 psi and 7,000°F. This energy was directed on a 4.5-gram model to propel it down a 20-millimeter bore. The gun measured a total of 35 feet in length. The muzzle opened into the evacuated test section, so a blast chamber with internal baffles and a vacuum connection was installed at the muzzle to attenuate blast effects and gas transmission into the test section.

In addition to varying the air density through the test section, its progressive enlargement functioned as the diverging portion of a Mach 5 supersonic nozzle. (Actually, the staff generally referred to the test section as "the nozzle.") Thus, the air speed was highest and density the lowest right where the model entered the test section, and the speed decreased while the density rose as the model progressed through the test section, closely simulating the varying conditions an entry vehicle would encounter. Aerodynamic resistance also slowed the model's speed, just as it would the vehicle. A model catcher located inside the air reservoir captured the model at the end of its flight. It was filled with a soft material that stopped, but rarely damaged, the model, enabling its post-flight examination.

The nozzle design determined the simulated altitude range of 130,000 feet, but the specific altitude range was selected by varying the initial reservoir pressure between 100 and 600 psi. A remotely operated plunger rupturing a copper diaphragm at the reservoir's exit initiated airflow into the tunnel. Unlike most counterflow tunnels, the AES had enough air stored that approximately 0.1 second could be allowed after the diaphragm's rupture for the flow to stabilize before the launch gun was fired.

HISTORY

The development of the first American intercontinental ballistic missiles, particularly the Atlas, during the 1950s pushed the understanding of reentry performance into a practical necessity. By the middle of the decade, H. Julian "Harvey" Allen's blunt-body concept had been accepted as the best design for reentry vehicles, but much still remained to be learned about the aerothermodynamic behavior of such vehicles. Flight testing was difficult, expensive, and time-consuming, so a ground-based test method was badly needed.

Ames researcher Alfred J. Eggers, Jr., tackled the problem theoretically. Employing the concept of similitude, Eggers ultimately defined the necessary conditions for a ballistic facility that could simulate the aerodynamic forces and heating on a reentry vehicle. The model would have to fly at full-scale speed to obtain the required Reynolds number, and the atmosphere would need to be tailored to simulate actual conditions. This meant a test section containing air at a relatively low temperature that also varied in density to match the changing altitude of the entering warhead. Eggers envisioned the combination of a hypervelocity gun, a device then under development at Ames, with a long supersonic nozzle. Using the diverging portion of the nozzle as the test section would produce the needed density variation. Eggers published his analysis and conceptual design in 1956.[137]

Ames management subsequently approved construction of a pilot facility to verify Eggers's concept and determine if such an apparatus had practical use. Carlton Bioletti, an Ames engineer and researcher, built the Small-Scale Atmospheric Entry Simulator using a 0.22-caliber light-gas gun and an 8.5-foot-long nozzle/test section that simulated a 100,000-foot range of altitude. The results were promising, and management authorized a permanent facility.[138]

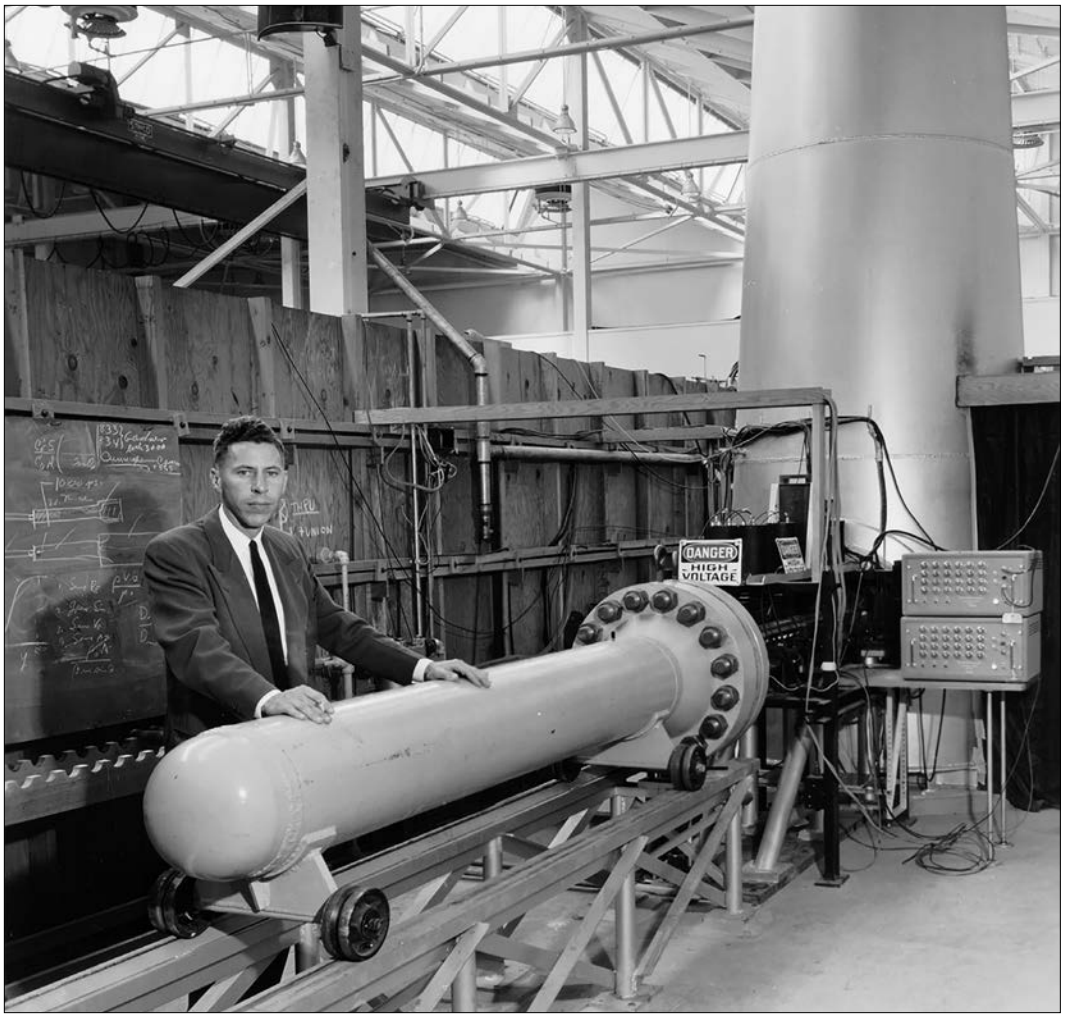
The AES entered service in 1958, just as the NACA was being folded into the newly formed NASA. Early tests using a model of a complete missile body showed excellent agreement with calculated values, and they demonstrated the validity of Eggers's analysis and concept. As he had predicted, most of the missile's velocity and almost all of its aerodynamic heating occurred in approximately 100,000 feet of altitude, the range covered by the AES. The models, made of ethyl cellulose plastic, also exhibited evidence of ablation. Pre- and posttest weighing determined the weight loss, and the model's posttest profile was compared to a template with an optical comparator to ascertain the ablation pattern. With the success of the missile tests, researchers began working with heat shields of designs suggested by Harvey Allen's earlier work. Most of these were ablation shields, where heat that reached the body was absorbed and shed by material evaporation and sublimation, sacrificing a heat shield to protect the remainder of the vehicle. Many of the early models tested in the AES used a copper plate bonded to a nylon cylinder that could be launched without a sabot. These tests validated computational predictions about heat transfer in such a shield and pointed to contours that reduced the temperature difference between the center and edge of it. As more advanced ablative materials were developed, they were initially tested in the AES.[139]

While the AES was an innovative solution to a difficult problem in 1958, it had its limitations. Even though it could produce speeds of over 13,000 mph, this was significantly below the 17,000 miles per hour—and greater heat—that would be experienced by spacecraft returning from orbit. As in all ballistic ranges and tunnels, test duration was on the order of milliseconds. The results matched calculated performance predictions

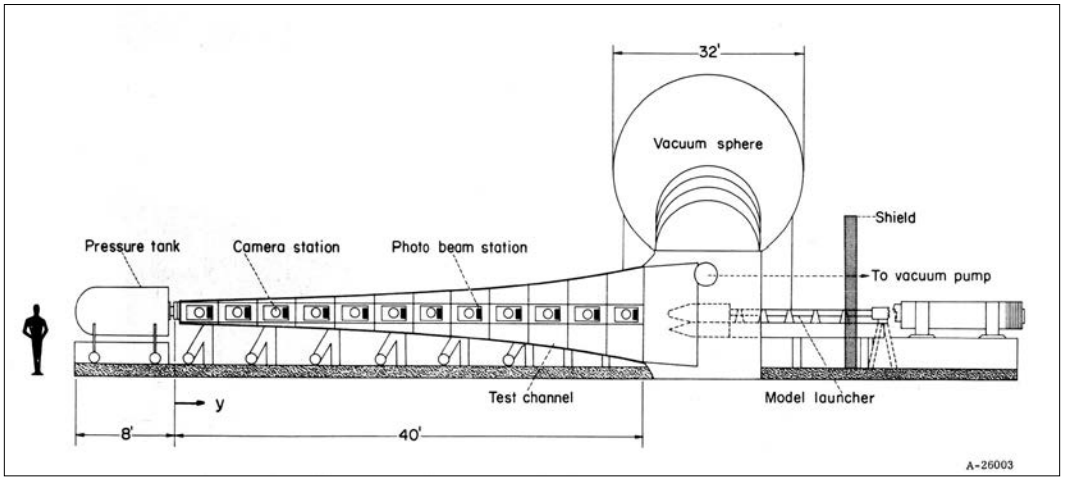
well, but many still had concerns over whether vehicles and materials experiencing a several-minute reentry would endure that much exposure time.

Parallel to the AES's development, another group at Ames was developing the arc-jet, a new device capable of generating the high-temperature environment needed for several minutes. An arc-jet consisted of a blowdown tunnel that passed its air through a high-power electric arc just ahead of its super- or hypersonic nozzle. The air stream blew into a large chamber where a model was inserted into the hot, high-speed flow. This air then exhausted to a vacuum sphere or, later, a steam-driven ejector. Much of the development work centered on optimizing the shape and nature of the arc to maximize heat transfer to the air. Ames's first arc-jet was completed in 1960, and an improved version that could generate enthalpies of up to 12,000 British thermal units per pound of air opened a year later. Further improvements more than doubled this figure by 1962, making arc-jets easily able to simulate the aerothermal conditions of spacecraft returning from the Moon at 25,000 miles per hour.[140]

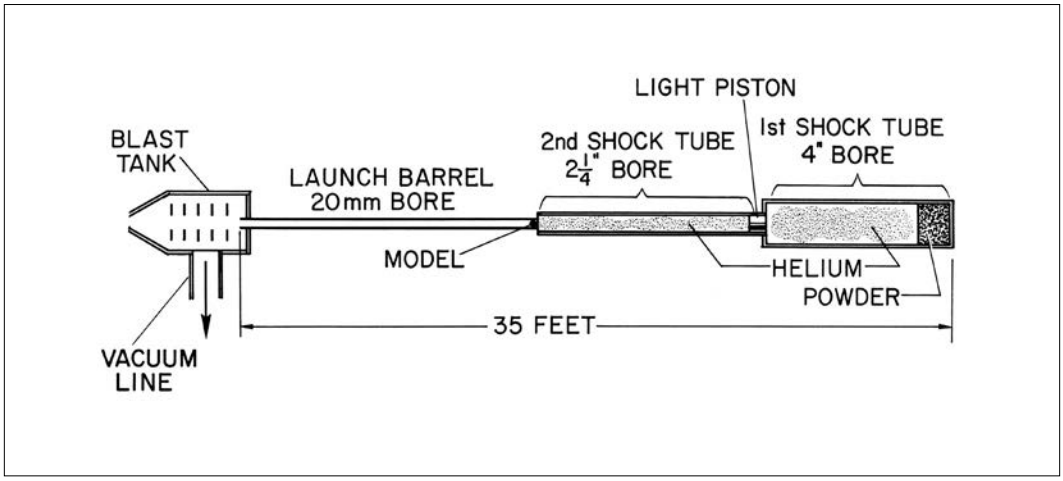
With this capability available, use of the AES rapidly diminished. Concurrently, use of the Hypervelocity Ballistic Range also decreased, and changing priorities indicated that the building could be better utilized by other activities. Consequently, the AES was removed by 1967. No portion of it is known to survive. Building N-223 currently hosts several materials development laboratories.



Alfred Eggers, Jr., standing beside the Small-Scale Atmospheric Entry Simulator, a pilot counterflow ballistic tunnel built to validate his concept that a model shot through air that was flowing through a hypersonic nozzle would simulate the conditions a spacecraft might encounter reentering Earth's atmosphere. Its successful operation led to the construction of the larger, faster Atmospheric Entry Simulator. (Photo credit: NASA A-23513)

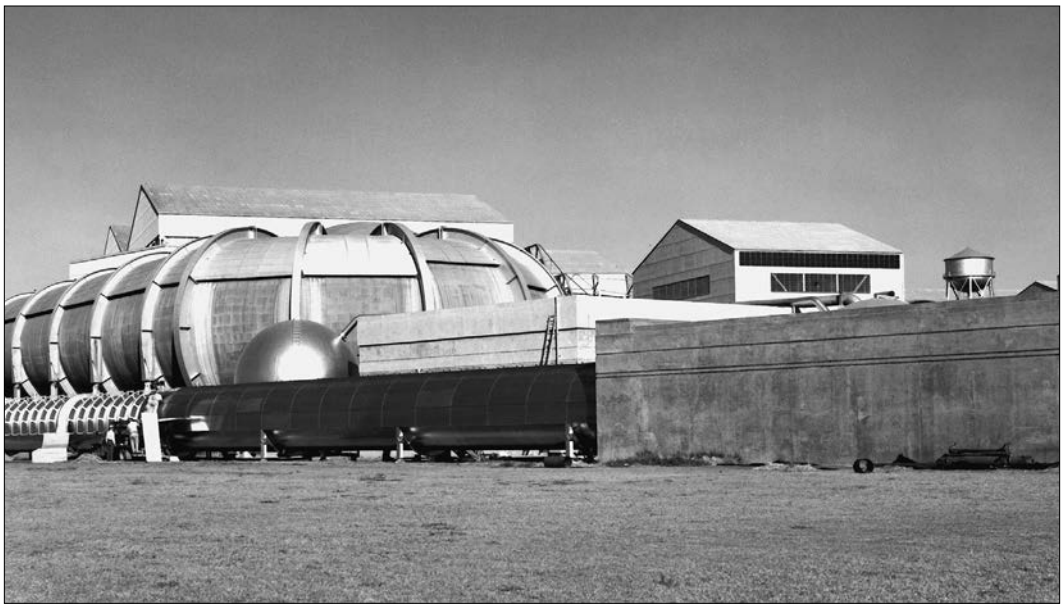


This drawing shows the basic arrangement and size of the Atmospheric Entry Simulator, along with its major components. The shield was actually one of the building's concrete interior walls, and the vacuum sphere (not to scale) was located outside. (Image credit: NASA TM X-394, Fig. 1)



This two-stage light-gas gun (top) launched models into the Atmospheric Entry Simulator at approximately 13,600 mph. The design differs from earlier light-gas guns by the addition of the second shock tube and relocation of the piston (bottom). The blast tank attenuated most of the gun's gas effects before they could enter the test section. (Photo and image credit: NASA A-24639-006 and NASA A-24639-005)

PRESSURIZED BALLISTIC RANGE



This 1957 view of the Pressurized Ballistic Range shows the concrete gun room at right with the partially covered tank extending to the left. A permanent, metal sunshade would soon cover the entire tank. Portions of the 12-Foot Pressure Tunnel and the 40- by 80-Foot Full-Scale Tunnel (now part of the National Full-Scale Aerodynamics Complex) are visible in the background. (Photo credit: NASA A-22970)

SIGNIFICANCE

The Pressurized Ballistic Range (PBR) was built on the success of earlier ballistic ranges at Ames to enable free flights of models in quiescent air at speeds from low subsonic to 7,500 miles per hour. It was the first ballistic range to operate under pressure, which allowed it to generate test conditions with high Reynolds numbers.

DESCRIPTION

The PBR was not a wind tunnel in the classic sense of blowing air past a stationary model, but even though most ballistic ranges are used for impact studies, this one was used effectively in aerodynamic research at Ames, so it is included here. Identified as Building N-209, the largest portion of the PBR was a cylindrical steel tank with semi-elliptical ends, which measured 225 feet long by 10 feet in external diameter. The tank is under a corrugated metal sunshade for its entire length to minimize solar effects, and it was supported by seven pairs of steel legs integrated into circumferential rings. The middle legs that anchor the tank were diagonally braced against longitudinal movement, while the other legs allowed for thermal expansion and contraction. One access hatch to the tank was located on its north side, approximately 40 feet from the east end. Enclosed within a vestibule that was part of the sunshade, the tank hatch was a pressure door with multiple clamp-type latches. Initially, the tank's operating pressures ranged between

0.01 and 10 atmospheres (0.15 to 147 psia). Though the records are inconclusive, this upper limit may have been reduced to 5 atmospheres (73 psia) in 1974, and again to 2 atmospheres (29 psia) by 1982.[141] The facility was demolished in the late 1990s.

Internally, the tank's 203-foot-long test section was divided into 24 sections, with the optical fields of view ranging from 1.5 to 5 feet high by 1.5 feet wide, spaced between 7 and 14 feet apart.[142] Bulkheads that had circular openings along the tank's centerline provided a clear path for model flight and separated these sections. The bulkheads served as both light and blast shields, and the interior of each section was painted flat black to minimize light reflection. Each section formed a shadowgraph station to photograph a model as it flew by. The system used in the PBR, known as an orthogonal shadowgraph system, used a photocell that detects the presence of the model at each station to simultaneously fire spark lamps above and beside the station. Each spark lamp projected a flash of light, and the shadow patterns produced by the model and differences in air density were recorded on film platens directly across from the two spark lamps. A variety of devices to catch models with minimal damage could be fitted at the west end of the tank, along with calorimeters to measure the heat in the model generated during the test.

At the tank's east end was an L-shaped, single-story concrete structure that enclosed the facility's control and gun rooms. The smaller portion with several doors and windows housed the control room, while the windowless larger portion provided space for the gun that fired models into the tank, as well as the shop area that supported the tunnel's operation. An overhead monorail hoist ran the length of the gun room and penetrated the wall over a door on the building's east end, the only wall penetration in the gun room portion of the structure. The gun room's bunker-like construction was a safety precaution due to the explosive materials employed in the launching gun.

When the PBR was in service, a 0.50-caliber light-gas gun launched models at speeds of up to 11,000 feet per second (7,500 miles per hour). The guns normally used in the PBR were a pair of 44-mm (1.74-caliber) and 61-mm (2.40-caliber) powder guns, which could launch model-caliber) up to 57 millimeters (2.24 inches) in diameter and weighing as much as 170 grams (0.375 pounds) to speeds approaching 5,500 feet per second (3,750 miles per hour).[143]

HISTORY

By the mid-1950s, engineers and researchers at Ames had developed ballistic testing technology to a high level of refinement and employed it in a variety of hypothetical hypersonic scenarios. Thus, when American concepts for intercontinental ballistic missiles and human spaceflight began to progress into the hardware stage, these same engineers and researchers turned to their ballistic experience to design facilities that could help design vehicles able to survive atmospheric reentry at speeds above Mach 10 in a predictable manner. One of these facilities was the PBR.

Thomas Canning, Alvin Seiff, and their team had developed effective tools and techniques for ballistic testing in a counterflow tunnel after completing the Supersonic Free-Flight Wind Tunnel (SFFWT) in 1949, but they had also come to understand its limitations, which included a significant amount of turbulence in the airstream. To be sure they fully understood any stability errors introduced by this turbulence, they needed a facility that could produce speeds of up to approximately Mach 10 in quiescent air and at high Reynolds numbers. The most practical solution appeared to be a ballistic range, using small models propelled by a light-gas gun. Pressurizing the test section would increase the Reynolds number.

With a cost of less than $1.3 million, Canning and Seiff received approval for the PBR quickly. They finalized their design and initiated construction in 1957. Unlike many projects at Ames, the PBR was straightforward to build, so construction proceeded rapidly. With their experience in the SFFWT, Canning and Seiff were able to set up the range quickly, and the PBR entered service in 1958.[144]

The light-gas gun, which was being developed at Ames during the same time the engineering team was starting to design the PBR, figured prominently in the PBR's design. In basic terms, a light-gas gun uses an explosive charge, usually gunpowder, to propel a piston along a pump tube containing hydrogen or helium, compressing the gas. At the end of the pump tube is a rupture disk designed to burst cleanly at a set pressure. This allows the high-pressure gas to flow into a much-smaller-diameter barrel, into which a projectile, in this case a model or model-sabot combination, has been placed. The compressibility of the gas allows it to concentrate the powder's energy and then release it into the smaller barrel, effectively amplifying the force on the projectile and accelerating it down the barrel. An important modification, also developed at Ames, was the use of a piston made of an engineering plastic, typically high-density polyethylene, that deformed as it moved against a taper at the end of the pump tube. This interference and deformation assured that virtually no leakage could flow around the piston, and the tapered end improved gas flow into the barrel.[145]

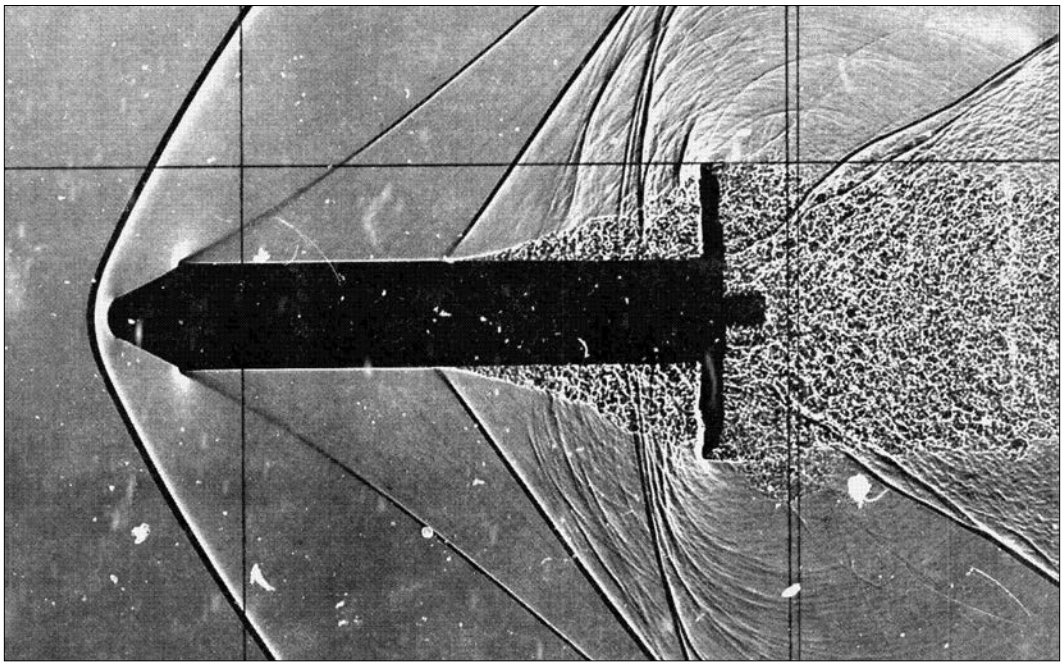
For the PBR, the team employed a light-gas gun with a 0.50-caliber (57-millimeter-diameter) barrel that could accelerate a 170-gram (0.375-pound) model up to a maximum speed of 11,000 feet per second (7,500 miles per hour). In practice, many tests required lower speeds, which could often be achieved by using a powder-charge gun alone, a substitution that more than doubled the model's velocity range. Available specifications for the PBR do not list a minimum launch speed, preferring to state, "low subsonic speeds."[146]

Relying on shadowgraphs to be the primary means of recording tests, the engineers adopted the method developed in the SFFWT. Since the PBR's operating environment was different, they exchanged the SFFWT's equally spaced shadowgraph stations for stations placed at varying intervals to better accommodate the model's deceleration during the test. A second useful instrument used in the PBR was a calorimeter to measure

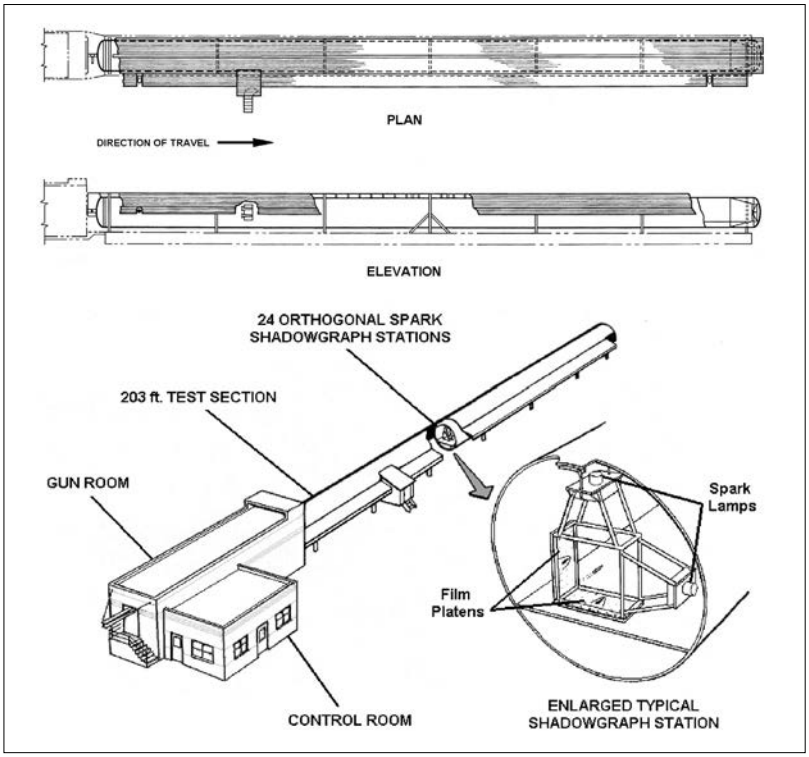
how much thermal energy a model gained during its flight. Most of the models tested in the PBR were made of polycarbonate, polyacetal, or other engineered plastic whose aerothermodynamic properties differ from those of aircraft and spacecraft metals but are easier and cheaper to produce. Testing a metal model and using the calorimeter to measure the heat gain provided a control reference for the plastic models. Early testing also demonstrated that radiation from the leading shock, often called the "gas cap," around the model would fog the shadowgraph film, which limited the maximum useful speed for certain tests.

The PBR proved to be useful for more than serving as a control reference for counterflow tunnels regarding turbulence effects. It was well suited for aerodynamic studies of blunt, ablating vehicles, including strategic warheads and probes sent to other planets, including Venus, Mars, and Jupiter. The PBR also hosted some early tests concerning the practicality of recovering expended solid rocket boosters for the Space Shuttle Program.[147]

In common with most other hypersonic research facilities, the PBR's bookings reflected the ebb and flow of hypersonic and interplanetary space programs, and the facility saw little use after 1990. The date of the PBR's closure is uncertain, but it was during the 1990s. The gun components and experimental equipment were subsequently removed for use elsewhere at Ames. The last aeroballistic test program conducted in the PBRF was in support of the Aero-assist Flight Experiment (AFE) circa 1987.[148] The last recorded testing activity conducted in N-209 appears to be a research project done jointly with Stanford University's Department of Aeronautics and Astronautics during 1994–95 to design and build a 1.5-inch high-pressure shock tube pilot facility. The existing steel rail that had supported the light-gas/powder guns served to support the new device, and the gun room's heavy construction shielded the surrounding area from a potential accident. Fortunately, none occurred, and the experimental apparatus was removed upon completion of the project.[149] The PBR has since been demolished, and all that remains is a parking lot north of Building N237.



Testing of a model at Mach 3.5 in the Pressurized Ballistic Range to determine aerodynamic characteristics of a proposed recoverable Space Shuttle booster vehicle. (Photo credit: NASA TM X-62124, Fig. 5)



These drawings show the Pressurized Ballistic Range's general arrangement, the sunshade over the tank, and a detail of one shadowgraph station. Note the single access door in the side of the tank. (Image credit: NASA TM-108691, Fig. 1-35)

HYPERVELOCITY FREE-FLIGHT FACILITY

The Aerodynamic Hypersonic Free-Flight Facility in 1976. (Photo credit: NASA AC76-1045)

SIGNIFICANCE

The Hypervelocity Free-Flight Facility (HFFF), which began operation in 1966, is NASA's only remaining aeroballistic capability and the nation's only current hypervelocity facility of its type capable of testing in gases other than air.[150] The HFFF possesses an arsenal of powder and light-gas guns that can provide model velocities that range from 0.2 to 8.0 km/s (500 to 28,000 ft/s). The facility is routinely used to test models with a wide range of geometries, masses, and base diameters under aerodynamic and aerothermodynamic conditions. The HFFF also possesses a large shock tube (currently inactive) for either counterflow aeroballistic testing or stand-alone shock tunnel operations, as well as a dedicated "gun development" facility that enables focused investigations intended to expand and optimize HFFF gun capabilities.[151]

DESCRIPTION

The HFFF occupies Building N-237, a heavily reinforced concrete structure that currently encloses two hypervelocity gun tunnels along with supporting shops and control rooms. These tunnels, the Hypervelocity Free-Flight Aerodynamic Facility (HFFAF)[152] and the Hypervelocity Free-Flight Gun Development Facility (HFFGDF),[153] comprise a set

of complementary tunnels that can interchange a variety of components, particularly model launching guns. The HFFF originally included a third tunnel, the Hypervelocity Free-Flight Radiation Facility (HFFRF), which was also a counterflow facility. In the 1980s, the original HFFGDF was demolished, along with the shock tube, nozzle, and test section of the HFFRF. The gun and blast chamber of the HFFRF were repurposed for gun development activities and rebranded the HFFGDF. In 2003, a new test section was constructed for the HFFGDF for aerodynamic testing.

The HFFAF, the larger of the tunnels, is a counterflow ballistic range capable of reaching test speeds of Mach 50; however, it has not been operated as a counterflow since the 1970s. The HFFAF has shadowgraph and timing devices for aerodynamic investigations, as well as thermal imaging (both visible and IR) cameras for aerothermodynamic investigations. These devices surround a test section, which lies at the center of the facility. In essence, the test section is a 23-m long tube approximately 1.2 m in diameter (actually, it is octagonal in cross-section and varies from 1 to 1.4 m between the flats with the cross-section expanding in the direction of the shock-tunnel counterflow) with 16 equally spaced (1.52 m) orthogonal imaging stations. Each station is equipped with a model detection subsystem and a set of high-precision reference wires. At one end of the test section lies the model launching gun and sabot separation chamber; at the opposite end lies the shock tube. The gun propels the launch package (model plus its carrier, also known as a sabot) into the sabot separation chamber, wherein the gun muzzle blast is attenuated, and the sabot separation process occurs before the model enters the test section.[154]

As the model flies by each imaging station, digital shadowgraph and/or thermal images are captured along with times of arrival. These data can then be used to determine aerodynamic and aerothermodynamic performance parameters of interest. In addition, high-speed video cameras can be used to observe and troubleshoot sabot separation processes and such. As mentioned previously, the HFFF light-gas guns can achieve model launch velocities of up to 8 km/s. For higher-speed investigations, the shock tube can be used to generate a counterflowing air stream into which the gun can be fired. The resulting, relative model velocity can be upwards of 11 km/s (lunar return conditions for both Apollo and Orion). The HFFAF can be, and has been, configured to operate as a shock tube, with a fixed model mounted in the test section, or as a hypervelocity impact facility.[155]

A second facility, the HFFGDF, is used primarily for gun-development testing. Unlike the HFFAF, the HFFGDF does not have a shock tube to generate gas flows. It employs the same guns as the HFFAF but has a smaller volume sabot separation chamber and a short test section. The HFFGDF can accommodate the same arsenal of guns: three powder type (20-mm, 44-mm, and 61-mm) and four light-gas type (7.1-mm, 12.7-mm, 25.4-mm, and 38.1-mm).[156]

The HFFRF, also a counterflow ballistics range, had an 80-foot-long shock tube and an 18-foot-long, 3.5-foot-diameter test section. There were four powder and light-gas

launch guns available: 0.28 caliber, 0.50 caliber, 1.00 caliber, and 1.50 caliber, with the longest measuring 145 feet in length. The HFFRF was equipped with radiometers to measure the thermal radiation emitted from a model's gas cap and wake.

HISTORY

The HFFF was constructed in the mid-1960s for the purpose of investigating the gasdynamic phenomena and problems associated with hypervelocity flight. As speeds increase above approximately Mach 10, compression and frictional heat raise the local temperatures of both the air and vehicle to levels that change their phase, physical properties, and even chemistry in ways that are almost always detrimental to the vehicle's survival. Some of the most difficult problems to comprehend and model accurately involve the chemical changes that occur in the gaseous environment (be it air for Earth entry or a different gas mix that represents the atmospheres of other planets) that surrounds a planetary entry vehicle. These changes, in turn, affect the aerodynamic and aerothermodynamic behavior/response of the entry vehicle. Investigating these high-energy phenomena and testing vehicle designs able to cope with them required a facility with energy levels not previously generated or used. Many at Ames and within NASA doubted that such a facility could be a practical tool, even if one could be built at all.[157]

About 1957, Thomas Canning and Alvin Seiff proposed a design to Ames management that they believed might generate the needed conditions. Their concept combined a hypervelocity light-gas gun with a counterflowing shock tunnel. Counterflow facilities were in successful operation at Ames, and they reasoned that higher speeds could be obtained by using a shock tube to generate the gas flow instead of a supersonic wind tunnel as previously employed. The concept was simple, but using a shock tube meant that such a facility would have test times no longer than a few milliseconds. The timing of the shock tube, model-launch gun, and camera shutters would have to be synchronized with incredible precision, but if these timing problems could be solved, such a tunnel might produce instantaneous test conditions of Mach 25 or higher. Ames management found it hard to believe that such precision could be achieved, but they allowed Canning and Seiff to try with a small, inexpensive pilot facility.

Using spare parts collected from around the center and as few purchased items as possible—essentially a "bootleg" project—Canning and Seiff built the Pilot Hypervelocity Free-Flight Facility (Pilot HFFF) in a temporary shed adjoining Building N-209 for only $27,000. The Pilot HFFF was a small, fairly crude device that used a light-gas gun to launch models of up to 7.1 millimeters (0.28 inches) in diameter at speeds of up to 19,000 miles per hour into a counterflowing air stream moving almost 3,700 miles per hour. Its 4-foot-long test section included two shadowgraph stations and a ring of narrow-band radiometers. A shock tube that used helium as the driver gas propelled the test gas, air or nitrogen dioxide (NO_2), through a Mach 6 nozzle. Though the Pilot HFFF's performance was well below what Canning and Seiff believed possible, it succeeded in proving the concept. It also appeared to be the only technology capable of testing reentry

vehicle designs at conditions like those to be encountered by spacecraft returning from the Moon and beyond.[158]

Ames's management was intrigued, but not yet convinced that spending $5 million to build the facility Canning and Seiff wanted would be worthwhile. They were, however, interested enough to authorize $375,000 for the engineers to build a larger version that, if successful, would be a prototype for a permanent facility. Canning and Seiff began work on the Prototype Hypervelocity Free-Flight Facility (Prototype HFFF), completing the facility in 1961. It improved on the Pilot HFFF in several ways, including higher pressure in the shock tube to produce almost triple the gas velocity in the test section; a 40-foot-long, 11-station test section; and the ability to launch models almost 70 percent larger. The test section design, with a vacuum chamber instead of a perforated blast blow-off section between it and the gun's muzzle, introduced an octagonal cross section that proved very successful. Its 11 shadowgraph stations were largely modeled on those of the Pressurized Ballistic Range. Several guns could be used to launch the models, with the largest being a light-gas gun with a 12-mm (0.47-inch) bore that could launch a 3-gram (0.1-ounce) model at speeds of up to 19,000 miles per hour. Using air or another nontoxic gas such as nitrogen dioxide, the shock tube could generate gas velocities of over 10,000 miles per hour, which produced a maximum test speed of approximately 29,000 miles per hour, or about Mach 40.

Like the Pilot HFFF, the Prototype HFFF performed well, even though it still fell short of Canning and Seiff's ultimate specifications. While the Prototype HFFF was a major improvement on the Pilot HFFF, they realized that additional improvements in both the shock tube and launching gun would be needed to achieve their goal of Mach 50, but continuing developments by them and others at Ames made this goal realistic. With this second success, management was finally comfortable with the concept's practicality and, in 1963, authorized $5 million to construct the HFFF.[159]

In addition to proving that Canning and Seiff's concept was practical, the Pilot and Prototype HFFFs hosted some valuable research work in their own right. They were, after all, the first two facilities of their type, and the space program needed answers to a host of hypervelocity questions as soon as possible. Much of this work involved studies of radiation and convective heat transfer from blunt bodies at high Mach numbers, as well as the energy radiated from the surrounding gas.[160]

Canning and Seiff immediately began design work on the HFFF in 1963, and construction started the following year. Drawing upon their experience with the Pilot and Prototype HFFFs, they produced a design for a facility with three tunnels. As they began their design work, advances in shock tubes and launch guns began to produce designs that could meet their 34,000-mph goal, but other problems remained to be solved. Chief among these were ultra-precise controls to make sure the model and slug of shock-tube-accelerated gas met at exactly the right time and place. They also realized that the existing shadowgraph technique could not produce sharp images in the HFFAF at these elevated speeds. This would require a device that could reliably control

exposure times to no more than about 40 nanoseconds. The solution used a Kerr cell, a small module containing benzonitrile (C_6H_5CN), a liquid that polarizes light when subjected to a high-voltage gradient across the module. At the time, available Kerr cells had response times of approximately 40 nanoseconds. Surrounding a Kerr cell with polarizing filters oriented 90 degrees apart in rotation yielded a high-performance shutter. Two polarizing filters set at a right angle normally block all light, but when an approximately 25,000-volt gradient is applied to the Kerr cell, it repolarizes the light from the first filter to match the polarity of the second filter, which allows it to pass through to the film. A high-speed, blue-sensitive film was used to capture the image, and this allowed the use of red safelights in the room after film had been loaded.[161] A spark lamp—actually a capacitive discharge spark gap—generated the exposure light, and each shot was triggered by a halogen lamp-photomultiplier device that came to be known as "Pandora's Box" because of its early problems.[162]

The HFFRF and HFFGDF opened in 1965, while another year was needed to complete the more complex HFFAF. Not unexpectedly, Canning and Seiff quickly found themselves dealing with several operating challenges. Some involved relatively simple model-launching and sabot-separation difficulties, but the shock tube proved to be the most troublesome component. Its problems included combustion variances that failed to generate a uniform mixture of propellant gases in the driver, as well as unsteady flow in the test section resulting from suboptimal shock tube operation. Minor changes in how the driver was charged and methodic variations of the shock tube's operational parameters reduced these problems to manageable levels and allowed the tunnels to generate useful data.[163]

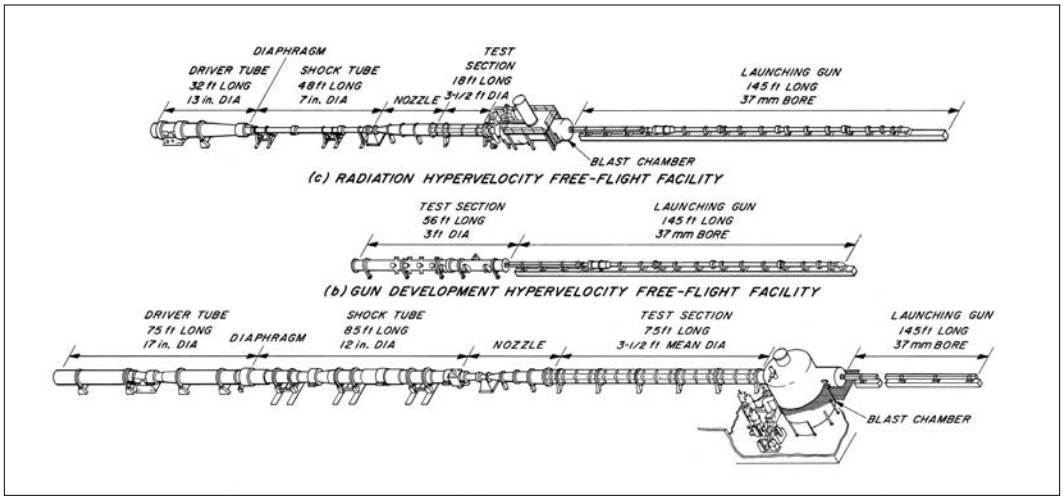
Some of the HFFF's earliest investigations focused on the process of ablation and the ways that thermal energy was created and released as it occurred. Since ablation removed material and changed the shape of the model, these investigations typically used both the HFFRF and the HFFAF to measure the thermal and aerodynamic effects. While it initially focused on reentry studies of the Apollo capsule and, later, the Space Shuttle, over the years, the HFFF's repertoire expanded to support studies of vehicle entry into the atmospheres of other planets, including Venus, Mars, and Jupiter. Such studies are possible because the HFFF tunnels can operate with any nontoxic test gas or mixture at sub-atmospheric pressures.[164]

Since the 1970s, NASA's human spaceflight program has concentrated on Earth-orbit missions that have reentry speeds below Mach 25. For such test programs in the HFFAF, the model launching guns have been used without the gas counterflow, making the test procedure less complicated. The HFFAF has also been used strictly as a shock tube, particularly to support scramjet research (National AeroSpace Plane, or NASP) between 1989 and 1994, and as an impact facility to test shielding materials for the International Space Station during 1995–96. In practice, the HFFAF has proved to be a more versatile facility than Canning and Seiff anticipated.[165]

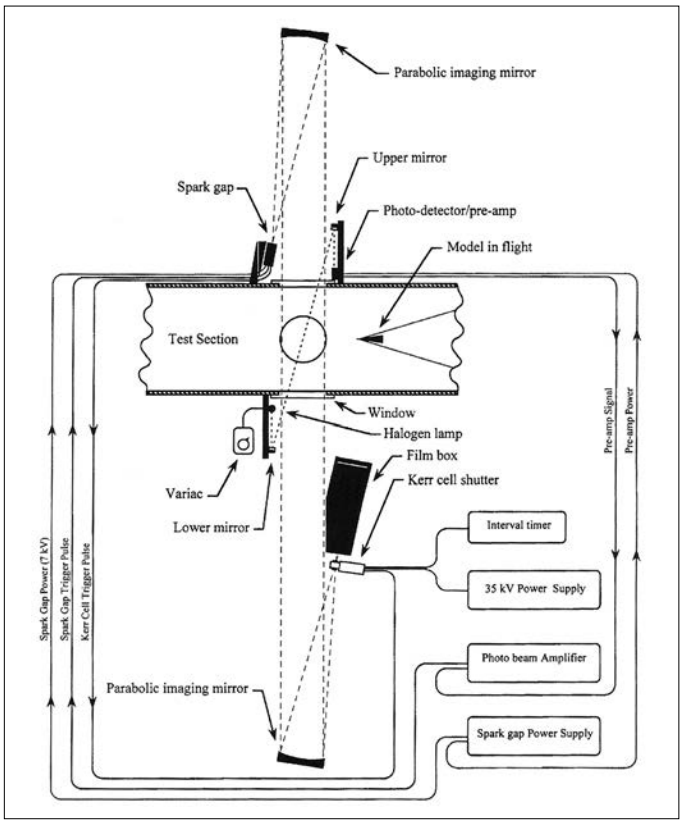
By 1996, three decades of service had taken its toll on the HFFAF, the most heavily used of the three HFFF tunnels. Limited to thermal radiation instrumentation research, the HFFRF had been closed by the early 1970s. Likewise, a reduced need for additional gun improvements had sharply curtailed the HFFGDF's utilization, although it remained in reasonably good condition. With an increasing interest in planetary probes, however, NASA conducted a review around 1997 that determined that the HFFAF was the agency's premier facility for planetary atmospheric entry tests. The resulting restoration program did not alter the tunnel's basic design, but it refurbished many of its model detection, spark lamp, Kerr cell shutter, and timing systems to restore the facility's reliability and performance.[166]

The Pilot HFFF was closed and dismantled about 1966. The Prototype HFFF remained in service until about 1970, after which it, too, was dismantled. Currently, both the HFFAF and the HFFGDF remain in service.[167]

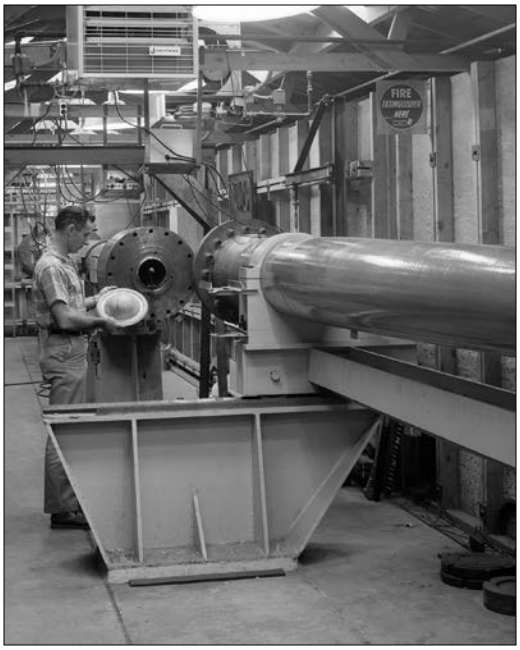
Development of the Hypervelocity Free-Flight Facility began in 1958 with the construction of the Pilot Hypervelocity Free-Flight Facility. The follow-on Prototype Hypervelocity Free-Flight Facility, completed in 1961, was housed in the building seen here in 1968. (Photo credit: NASA A-40781)



This pictorial drawing shows the original arrangements and relative sizes of the three tunnels making up the Hypervelocity Free-Flight Facility. The launching gun of (a) is actually the same length as the guns in (b) and (c). Other guns were available and interchangeable. Note that tunnel (b) and the shock tube, nozzle, and original test section of tunnel (c) no longer exist. (Image credit: NASA A-34717-5)

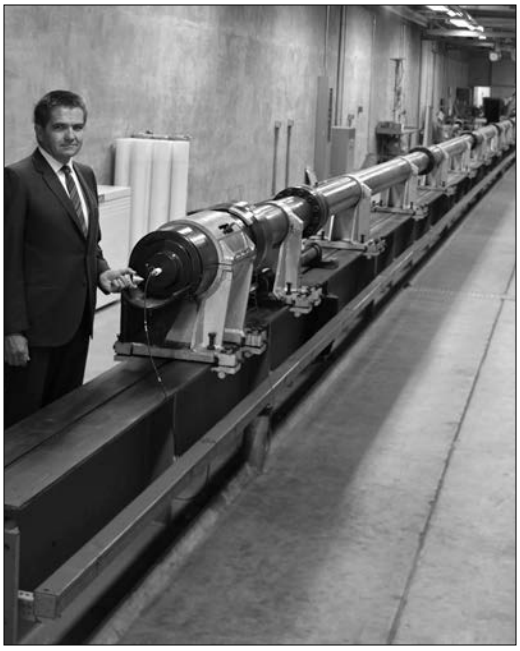


This diagram shows the complex system necessary to obtain shadowgraph images with exposure times of less than 40 nanoseconds. The Hypervelocity Free-Flight Aerodynamic Facility has 32 of these systems that furnish vertical and horizontal images at its 16 stations. (Image credit: NASA RTOP 242-80-00, Fig. 3)



A technician is replacing the diaphragm between test runs of the Prototype Hypervelocity Free-Flight Facility in 1963. Note how the shock tube portion rolled to one side for servicing. (Photo credit: NASA A-30556)

The test section of the Prototype Hypervelocity Free-Flight Facility, seen here in 1963, had 11 shadowgraph stations, with portions of them enclosed by pyramids. (Photo credit: NASA A-30557)



Branch Chief Thomas Canning standing beside a Hypervelocity Free-Flight Aerodynamic Facility light-gas gun in 1966, holding a typical model (left), and beside its combustion-driven shock tube (right). In the left photo, note the stacks of deformable plastic pistons for the light-gas gun against the wall. (Photo credits: NASA A-37249 and NASA A-37250)

This 2006 view of the Hypervelocity Free-Flight Aerodynamic Facility's test section shows it illuminated by red safelights that did not expose the 32 shadowgraph film panels (2 per station) prior to a test. Kerr cell shutters at each station open for a few nanoseconds to capture images of the model and surrounding flow field as the model passes. (Photo credit: NASA ACD06-0177-007)

This 2020 view of the Hypervelocity Free-Flight Aerodynamic Facility's test section shows the upgrade to digital shadowgraph cameras. Kerr cell shutters, still in use at each station, open for a few nanoseconds to capture images of the model and surrounding flow field as the model passes. Also seen are high-speed digital video cameras and infrared cameras on tripods. (Photo credit: NASA ACD20-0055-008)

1-FOOT HYPERVELOCITY SHOCK TUNNEL

The Hypervelocity Shock Tunnel in 1964. (Photo credit: NASA A-33038-9)

SIGNIFICANCE

The 1-Foot Hypervelocity Shock Tunnel (HVST) was an early combustion-driven shock tube that used a "one-cycle shock compression" process to produce test speeds over Mach 12 and maintain them for as much as 10 times longer than most shock tunnels.

DESCRIPTION

The HVST, also known as the Combustion-Driven Shock Tunnel, the Explosion-Activated Shock Tube, and the 1-Foot Shock Tunnel, was designed to generate shock velocities between 8,000 and 15,000 feet per second (5,450–10,200 miles per hour) for approximately 180 milliseconds, a long duration for shock tunnels. This was accomplished by employing a high-volume combustion chamber that supplied driving gas to a driven, or shock, tube through a pair of throttling plates at the junction of the chamber and the shock tube, which contained the test gas, to propel that air through a nozzle, followed by the test section, and into a vacuum tank.

The HVST was constructed inside an existing Quonset construction shed known as Building N-228. Because of the high energies involved, a U-shaped, double-wall, wooden barrier filled with sand was built within the building to isolate people and the surrounding equipment and gas-storage tanks from a high-pressure failure of any tunnel component. The tunnel's components were laid out in a straight line, with all of

its high-pressure elements within the barrier. To minimize electrical losses, the igniter's capacitor bank and charger also were within the barrier.[168]

The tunnel's combustion chamber resembled part of a large naval gun with internal measurements of 24 feet in length and 27 inches in diameter. This relatively large volume served to weaken any unsteady shock waves propagating through the driver gas. The vessel was charged with a gas mixture—typically 12 percent hydrogen, 7 percent oxygen, and 81 percent helium—at a pressure of 750 psi. Six thin wires of Manganin, a copper-manganese-nickel alloy, extended most of the chamber's length, and they were connected in parallel to a 10-kilojoule capacitor bank through high-voltage switchgear. Closing the circuit discharged the capacitors through the wires, instantly melting them and igniting the gas.[169]

The combustion chamber was separated from the 40-foot-long, 6.2-inch-diameter shock tube by a diaphragm and a pair of throttling plates, each with 36 0.875-inch holes that controlled the flow into the shock tube and gave the HVST its long test time. A powder charge propelled a punch to penetrate the diaphragm when the combustion-induced pressure peaked, which allowed the driver gas, a steam and helium mixture, to expand into the shock tube and accelerate the test gas it contained—usually dry air, though nitrogen, carbon dioxide, and argon were also used. A primary shock wave moved through the test gas in the shock tube until it reached the end and reflected toward the combustion chamber. On the return, this shock met and retarded the forward moving gas, thereby compressing it non-isentropically to a high pressure, temperature, and, hence, enthalpy, as it passed through. Since the process involved only one primary and reflected shock, it was referred to as a "one-cycle shock compression" process.

When the primary shock wave reached the end of the shock tube, it also ruptured a thin plastic diaphragm, which allowed the highly compressed test gas to flow through an axisymmetric nozzle, where it expanded and accelerated; it then passed through the test section and diffuser, and then into a 500-cubic-foot vacuum tank. The HVST's test section measured 1 foot square by 3 feet, 2 inches long, and it had rectangular observation windows mounted in bolt-on hatches on all four sides. Models were sting-mounted, and typical test times were 180 milliseconds. High-speed instruments measured and recorded static pressures throughout the tunnel, as well as dynamic pressure in the test section. Two quartz-crystal pressure transducers detected the primary and reflected shock waves. Velocity measurement used a spark to disturb the air, which was then photographed by a schlieren system to determine how far the disturbance had moved in a specific interval of time. Tests using a thermocouple fabricated as a hemisphere recorded temperatures and allowed heat-transfer rates to be calculated.[170]

HISTORY

The development of shock tunnels at Ames began in the late 1950s as missiles and spaceflight took on a growing prominence, and engineers and researchers realized that they needed tools that could simulate the extreme aerothermodynamic—a combination of

aerodynamic and thermodynamic—conditions of hypervelocity flight and atmospheric entry from space at speeds of Mach 25. Development work on hypersonic tunnels had been going on since the 1940s in the United States and abroad. Ames had opened its first such facility, the 10- by 14-Inch Hypersonic Tunnel, in 1950. It could achieve Mach 6.3 and taught the Ames researchers and engineers much about such tunnels and the hypersonic flight regime, but by the end of the decade, hypersonic research had extended into the hypervelocity regime,[171] and much higher test speeds were needed. This led Ames into designing, building, and operating tunnels capable of reaching speeds of Mach 10 and above.[172]

The development of ultra-high-speed tunnels took four parallel paths at Ames: blow-down wind tunnels, ballistic ranges, shock tubes/tunnels, and counterflow facilities that combined a ballistic range with a counterflowing wind or shock tunnel.[173] The primary proponents and developers of the shock tunnel concept were Bernard E. Cunningham and Samuel Kraus, who began work on a predecessor to the HVST called the Parabolic Entry Simulator (PES) about 1957. The PES was intended to be a hypervelocity successor to the Atmospheric Entry Simulator (AES) then under construction, but after the AES entered service, it soon became apparent that a device as specialized as the PES was not needed. Accordingly, Cunningham and Kraus turned their attention to the development of a practical shock tunnel.[174]

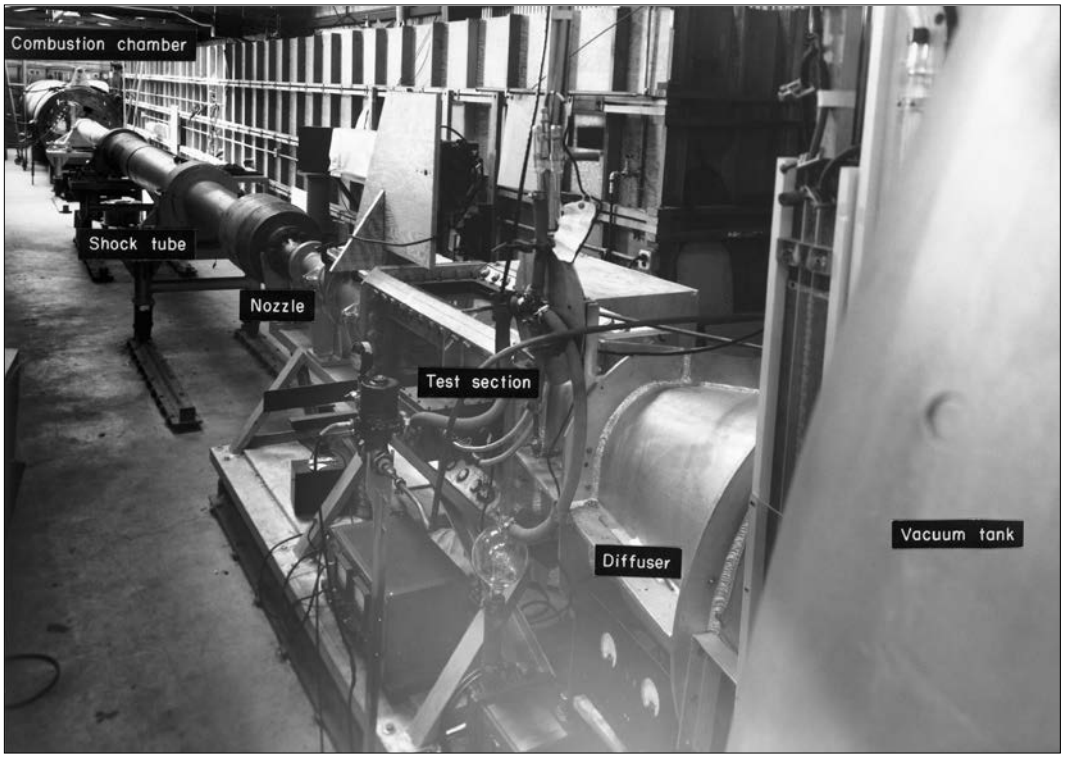
The two men completed the basic design of the HVST by early 1958, and construction began soon after. Typically, the prototype for a new concept at Ames would be built as cheaply as possible, using existing facilities and components wherever possible, and the HVST was no different. An existing Quonset building, erected as a temporary construction shed, housed the new facility, which became known as the Hypervelocity Airflow Laboratory. To contain the effects of a high-pressure leak or an explosive accident, workers built a double-wall, U-shaped barrier up to 6 feet thick inside the building and filled it with sand instead of the reinforced concrete style of barrier normally built for a permanent structure. Some of the supporting tanks and equipment came from elsewhere in the center, and existing computers processed the data.[175]

The HVST entered service in 1960, and it became the venue for a series of tests to determine its performance and validate the measurement techniques necessary for shock tunnels. These tests produced measured data and calculated values that, while not perfect, were in good agreement with theoretical predictions, indicating that shock tunnels could be useful tools for hypervelocity investigations. The HVST also served as a test platform for improving the technology, particularly in the area of ignition and stable burning of the driver gas mixture.[176]

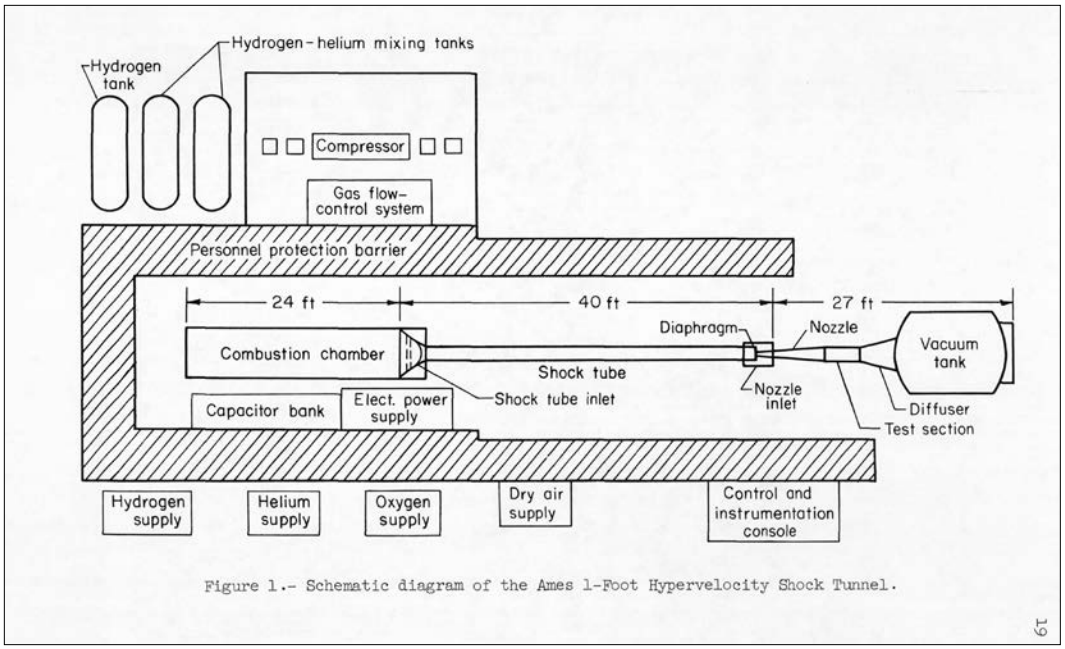
In 1967, a 42-inch test section and nozzle were installed to allow the tunnel to accommodate larger models. Able to generate enthalpy, a term for the total energy in the airstream, up to approximately 6,400 British thermal units per pound of air, the tunnel proved useful in the study of high-energy gasdynamics, but it was not easy or efficient to use. Each test run required about 8 hours of preparation, most of which was

cleanup from the previous test. The combustion of hydrogen and oxygen produced substantial amounts of water, and workers had to scrupulously clean the entire tunnel of water and other debris between runs.

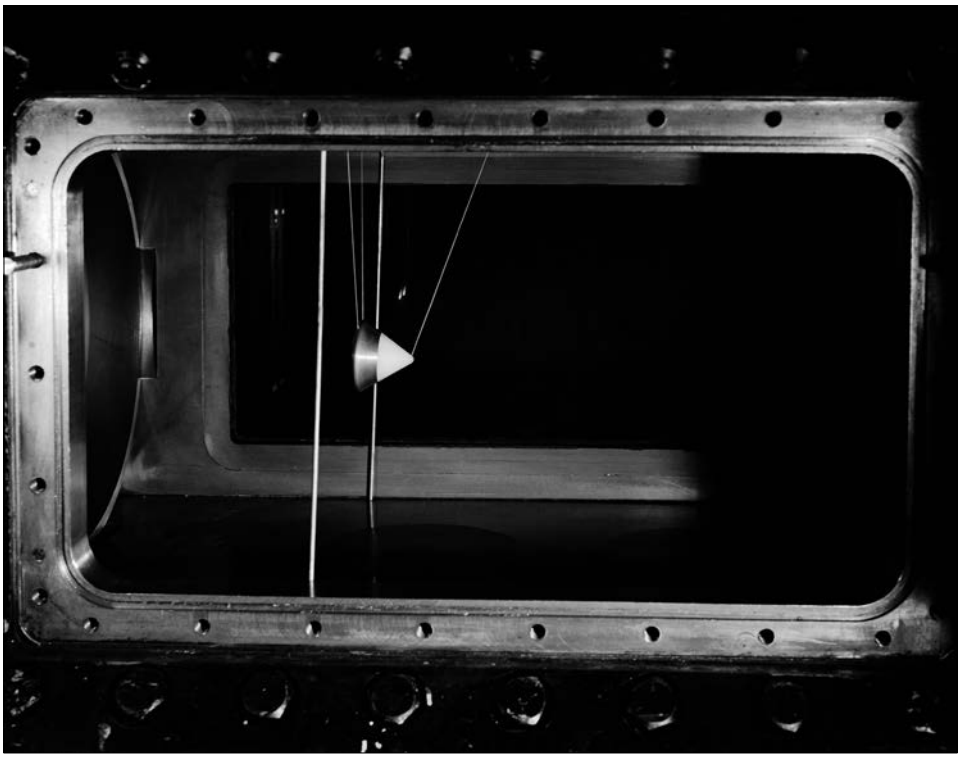
The HVST proved that the shock tunnel could be a viable tool for hypervelocity studies up to at least Mach 14, and its 180-millisecond test time was long enough to help develop increasingly accurate instrumentation for tunnels with shorter run times. It was, however, one of NASA's more short-lived facilities, as it and its Quonset shed home were demolished in 1972. While some of its components may have found other uses in the center, no identifiable portion of the HVST is known to survive.



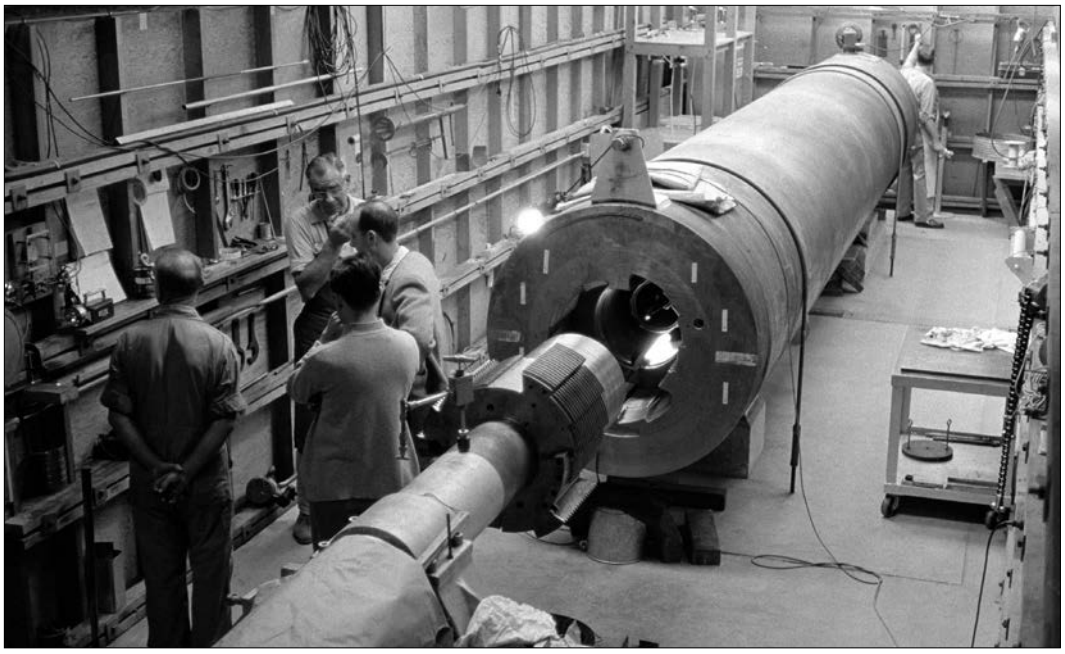
This overall view of the HVST in 1960 identifies its major components. Its flow was from upper left to lower right in this view. (Photo credit: A-26888_1)



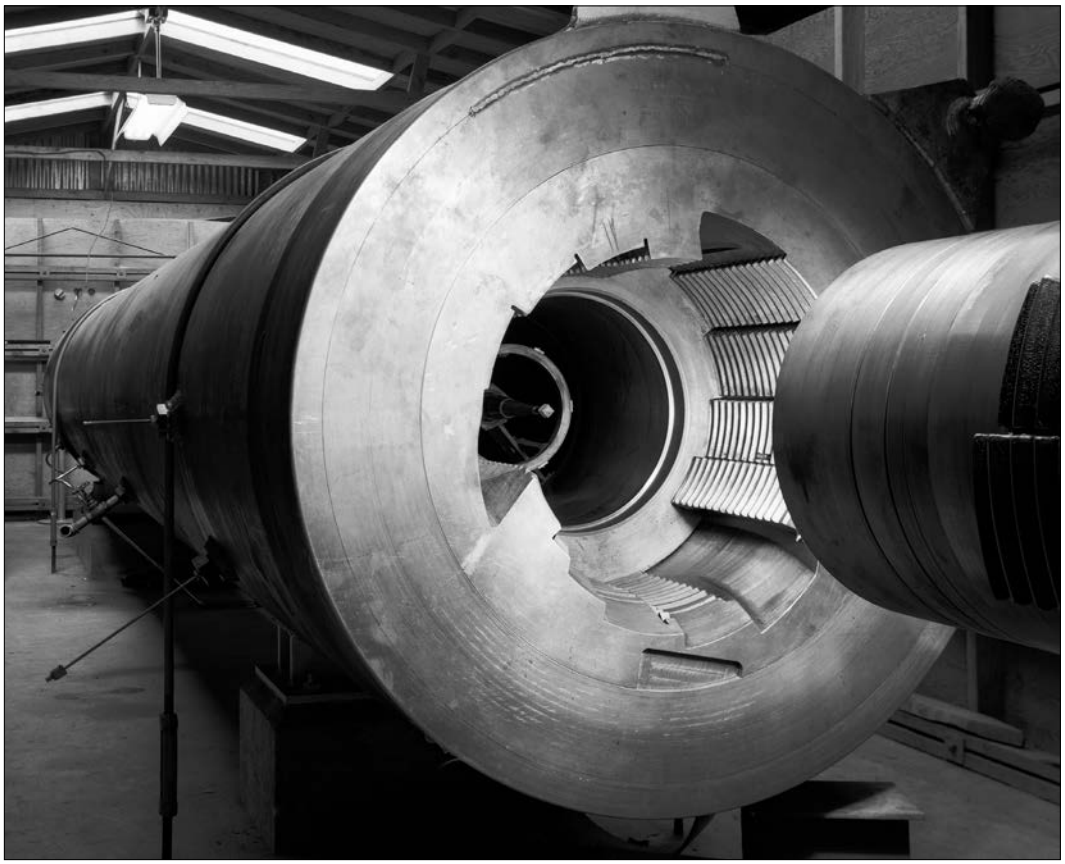
This plan drawing of the Hypervelocity Shock Tunnel shows its supporting equipment as built inside Building N-228. The personnel protection barrier was a wooden structure filled with sand. (Image credit: NASA TN D-1428, Fig. 1)



The Hypervelocity Shock Tunnel's test section is shown here in 1964 with its access hatch removed to reveal a blunt-body model mounted on a sting. The flow was from left to right. (Photo credit: NASA A-33794)



A mixture of hydrogen, oxygen, and helium ignited in the Hypervelocity Shock Tunnel's combustion chamber (top) produced the 5,000-pound-per-square-inch pressure needed to drive the tunnel. With the remainder of the tunnel pulled away (bottom), the interrupted-thread connection, similar to the breech of a large naval gun, can be seen. The throttling plates and diaphragm fit into this area. (Photo credits: NASA A-25889 and NASA A-26889)



3.5-FOOT HYPERSONIC TUNNEL

Four vacuum spheres dominate this 1977 aerial view of the 3.5-Foot Hypersonic Tunnel Complex. (Photo credit: NASA AC77-0846-43)

SIGNIFICANCE

The 3.5-Foot Hypersonic Tunnel (3.5 HYST) was the first large hypersonic tunnel built at Ames and NASA's first large hypersonic tunnel to utilize a pebble-bed heater. Employed to study all of America's crewed spacecraft, this tunnel performed approximately one quarter of all Space Shuttle wind tunnel testing.

DESCRIPTION

The 3.5 HYST was a blowdown tunnel that operated between a high-pressure source of air and a set of evacuated spheres. While the concept is simple, the extreme temperatures and pressures required to achieve speeds above Mach 5 in a wind tunnel made this tunnel anything but simple in execution. Building N-229 enclosed the central components, including the pebble bed heater, test section, nozzles, and control room. A two-story office building formed its south side. North of the building stood four steel vacuum spheres, which were connected to the tunnel's diffuser by steel pipes through a cylindrical aftercooler.

Auxiliary Equipment Building N-229A, located just east of N-229, housed two 5,500-horsepower air compressors that supplied 3,000-pound-per-square-inch air to a rack of 20 high-pressure storage bottles. A cryogenic separation plant conditioned and dried the air prior to storage. Both facilities, along with two cooling towers to cool water for the complex, were located north of N-229A. In 1975, installation of the Ames Underground Air Storage Facility augmented the bottle rack to provide a total

capacity of 33,000 cubic feet of air at 3,000 psi. This air system now serves as the primary compressed air supply for the center.

Hypersonic tunnels like the 3.5 HYST require incoming air to be heated, often to several thousand degrees, to prevent liquefaction of the air as it expands out of the nozzle's throat. The design engineers based the complex on a massive cylindrical device known as a pebble bed heater that they projected would deliver the necessary volume of air to the nozzle at 4,000°F, which was sufficient for Mach 14. The heater, fabricated from 8-inch-thick steel plate, is filled with 125 tons of high-temperature pebbles that were preheated by a natural gas burner before each run, a process that takes approximately 1.5 hours. Several pebble materials have been used. Air from the storage rack would flow through this heated bed on its way to the nozzle. Accordingly, the engineers designed the 3.5 HYST with four interchangeable nozzles for operation at Mach numbers 5, 7, 10, and 14. In practice, however, the pebble bed heater could not successfully raise the air temperature above 3,000°F, making the Mach 14 nozzle unusable.

From the domed top of the pebble bed heater, air flowed horizontally through the nozzle, test section, diffuser, and aftercooler, and into the vacuum spheres. Air from the vacuum spheres could be recovered by the compressors for storage and future use, thus reducing the amount of conditioning needed versus atmospheric air.

As built, the tunnel employed a 3.5-foot-diameter by 10-foot-long closed test section. It had an upwardly hinged door on each side that extended the full length of the section for model installation and access. This configuration was replaced with a larger cylindrical test chamber during a 1972 rebuilding of the tunnel. This 12-foot-diameter by 48-foot-long test chamber was perpendicular to the airflow. At its mid-point, the nozzle exhaust formed a 3.5-foot-diameter open jet that flowed across the test chamber and into the diffuser. The effective length of the core test area was approximately 10 feet. The test chamber was equipped with two personnel doors and a circular overhead hatch for access, all of which are pressure doors with seals and clamping latches. A remotely controlled mechanism within the test chamber inserted the sting and model into the test stream after it was established and extracted it at the end of each run. The sting's angle of attack could be continuously varied ±20 degrees during runs. Run times varied with the test conditions, but useful test durations between 30 seconds and 3 minutes were typical.

Instrumentation could include a six-component, strain-gage balance in the model and a number of pressure and temperature sensors. Cameras and shadowgraph cameras were generally mounted inside the test chamber to monitor tests and capture images of shocks. During the 1990s, several advanced techniques were installed for flow visualization, as well as for non-contact temperature and density measurements. Data were recorded electronically.

The three nozzles were mounted on a rail-borne cart that operators shift laterally to align the desired nozzle between the pebble bed heater and the test chamber. While each nozzle was contoured for a specific Mach number, the inlets and outlets of all three

were the same. Flanged joints allowed any of them to be bolted easily to the test chamber and heater. The nozzles were protected from the 3,000°F heat by a cooling system that circulated helium through the annular space of the double-walled structure.

Air leaving the test chamber entered a diffuser followed by an aftercooler, where the temperature was reduced to optimize the volume of the vacuum spheres. Water circulating through the aftercooler and two cooling towers transfered this heat to the atmosphere. Four steel vacuum spheres were pumped down to approximately 0.1 pound per square inch absolute pressure before each run, and the test air filled them during the run. Remotely controlled valves controlled the tunnel's flow and isolated the vacuum spheres as needed. A 1965 modification allowed the 3.5 HYST to use a variety of gases, such as carbon dioxide, nitrogen, and mixtures, in lieu of air. This capability allowed the tunnel to simulate entry into other planets' atmospheres.

All of the tunnel's operations were managed from a control room on the west side of the building, and an adjacent room housed the supporting control and data acquisition equipment. In the original configuration, windows in the control room wall and test section access doors allowed the direct observation of tests. Since the 1972 rebuilding, direct observation has not been possible, so video cameras inside the test chamber transmitted live feeds to monitors in the control room.

HISTORY

During the 1950s, the NACA began to seriously investigate hypersonic (Mach 5 and above) aerodynamics, driven in part by the need to understand the conditions that ballistic missile warheads would experience when reentering the atmosphere and how such vehicles would perform. By the end of the decade, hypersonic research had extended into the hypervelocity regime, and it had taken several parallel paths, with Ames concentrating on the aerothermodynamic—a combination of aerodynamic and thermodynamic—problems of reentry while Langley and Lewis focused on hypersonic cruise and propulsion respectively. This led Ames into the realm of designing, building, and operating tunnels capable of reaching speeds of Mach 10 and above.

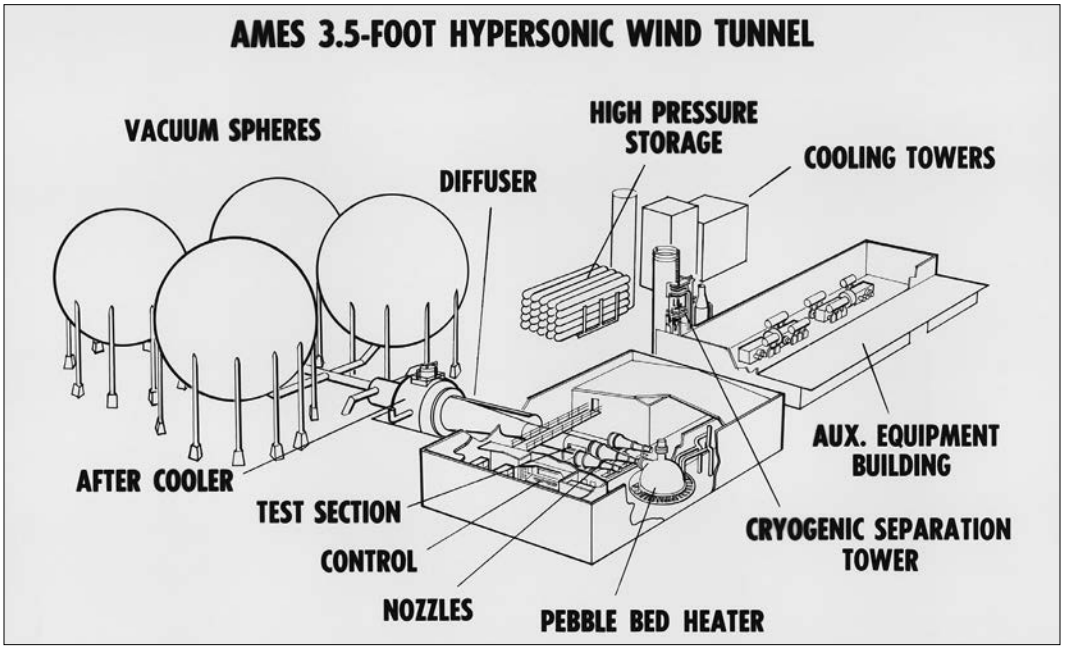
In 1957, Clarence A. "Sy" Syvertson and Alfred J. Eggers, Jr., two of the more-prominent hypersonic researchers at Ames, began designing a tunnel that would provide significantly greater capabilities than the 10- by 14-Inch Hypersonic Tunnel (10- by 14-Inch HYST) that Eggers, Syvertson, and others had been using since 1950. While the 10- by 14-Inch HYST had been useful, the operation of it had identified a number of deficiencies, including its maximum speed of Mach 6.3, its small size, and operational problems with the variable-speed nozzle. The researchers also wanted a facility that could sustain high Mach numbers for at least 30 seconds instead of the millisecond run times available in shock tubes and other impulse-type tunnels. Satisfying these specifications required the construction of an all-new facility and air-supply system with a total price tag of almost $13 million, second only to the cost of the Unitary Plan Wind Tunnel at Ames.

With the large number of unknowns in the project, Syvertson and Eggers's team decided to build a pilot tunnel to verify the predicted performance of the pebble-bed heater as well as the overall design concept for the tunnel. They built this pilot tunnel, which used a smaller version of the underground pebble-bed heater to feed a 1-foot-square vertical test section and atmospheric exhaust, in Building N-205. The pilot tunnel utilized compressed air into the heater at 50–2,000°F, and the heater, ultimately filled with yttria-stabilized zirconia open-core firebricks was designed to output this air at up to 4,200°F for speeds of up to Mach 12. In spite of the heater's capability, only a Mach 5 nozzle was ever used. The pilot tunnel's performance indicated that the calculations for the full-sized tunnel were sound, and it remained in service hosting a variety of small-scale projects until the late 1960s.

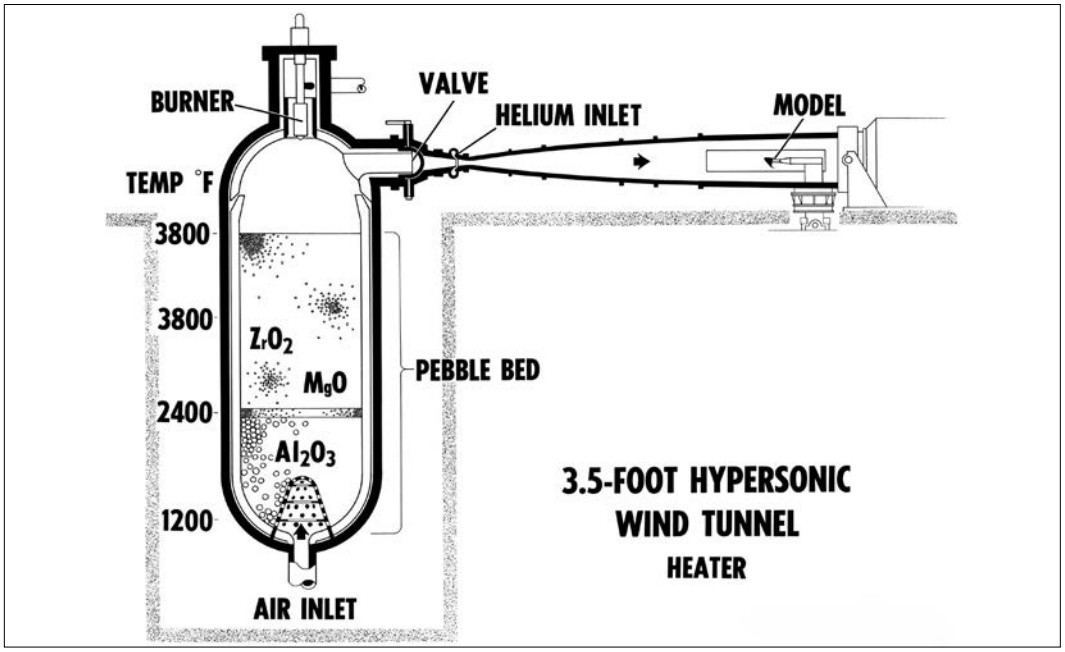
Upon its completion in 1961, the researchers immediately began to test and calibrate the 3.5 HYST. The initial charge of aluminum oxide and zirconium oxide pebbles in the heater performed well up to the 3,000°F needed for the Mach 5, 7, and 10 nozzles, but raising it to 4,000°F for Mach 14 quickly exposed some serious problems. The worst of these, and the one not readily overcome, resulted from the pebble materials' propensity to shed fine ceramic dust particles at temperatures above approximately 3,500°F. This abrasive dust rapidly sandblasted the Mach 14 nozzle into a useless contour. Tests in the pilot tunnel's heater indicated that open-core firebricks made of yttria-stabilized zirconia would likely work, but without better assurance of success, Ames's management declined to approve the costly conversion. Thus, the 3.5 HYST's top speed remained Mach 10.

Like most of Ames's tunnels, the 3.5 HYST has been the venue for pure research and vehicle development test programs. Interest in hypersonic research has ebbed and flowed over the years, primarily due to federal spending, or the lack of it, on various space and aerospace projects during different periods. Project Apollo clearly drove the 3.5 HYST's construction, and the tunnel hosted almost one-quarter of all Space Shuttle wind tunnel tests during the 1970s and 1980s, along with tests of the proposed National Aero-Space Plane (NASP) between 1985 and 1995. Between periods of intense development testing, researchers used the tunnel to investigate the behavior of a variety of hypersonic flow fields. Many of these tests were designed to generate data for or validate computational fluid dynamics (CFD) code, whose developers were just beginning to incorporate thermodynamic behavior into their codes during the 1980s.

When the government canceled the NASP program, the 3.5 HYST's bookings dropped dramatically, and the tunnel became a candidate for closure in the 1990s under NASA Administrator Daniel S. Goldin's "full cost accounting" program. But the 3.5 HYST possessed some unique performance qualities that could be only partially met in other American hypersonic tunnels, and some, including the military, believed its capabilities would again be needed in the future. Accordingly, the 3.5 HYST was mothballed about 1999, but it was maintained essentially intact for a number of years. The HYST and its vacuum spheres were removed circa 2015, and all that remains is the pebble bed and part of the control room.



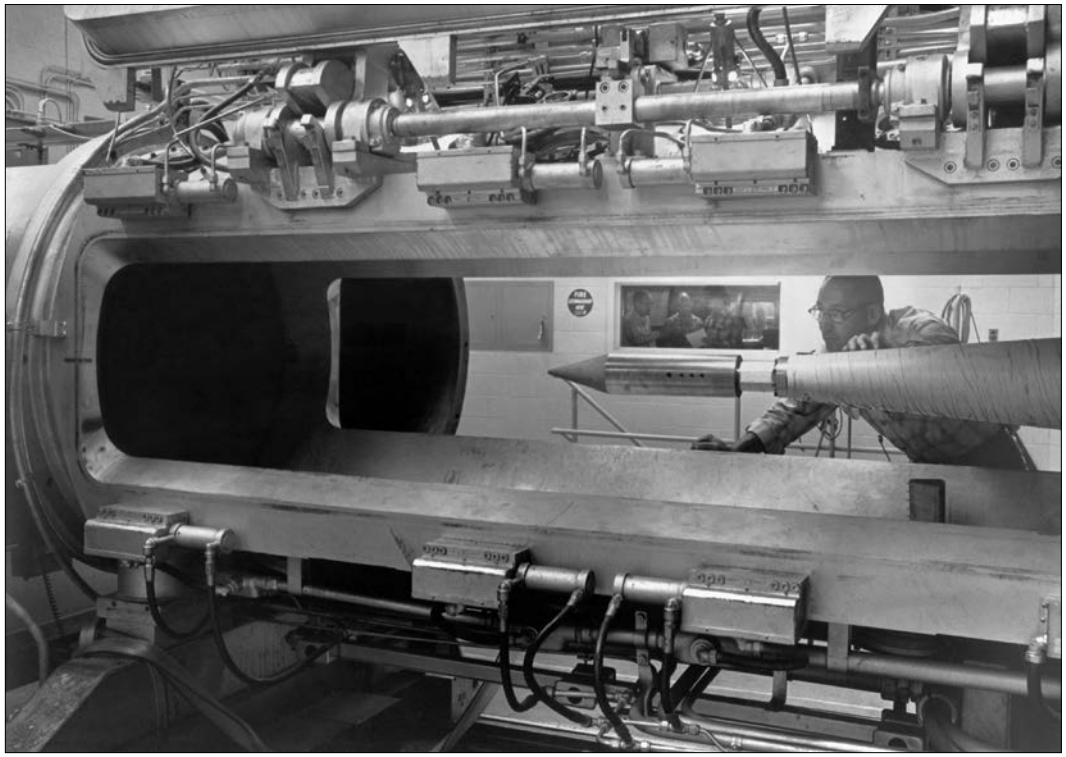
This 1961 cutaway drawing of the 3.5-Foot Hypersonic Tunnel as built identifies all its major components. Only the top of the pebble bed heater, which extends four floors down, is visible. Note the three interchangeable nozzles for Mach numbers 5, 7, and 10. (Image credit: NASA A-28418)



Schematic drawing of heater for the 3.5-foot Hypersonic Wind Tunnel. (Image credit: NASA A-28420)

The 3.5-foot Hypersonic Wind Tunnel in 2012. (Photo credit: NASA ACD12-0111-002)

A Space Shuttle orbiter model is shown here in 1973 mounted on a sting for testing inside the test chamber. The seam visible inside the nozzle's exit marks the edge of one of the three interchangeable nozzles. (Photo credit: NASA AC73-5027)



A technician inspects a model in the 3.5-Foot Hypersonic Tunnel's original test section in 1961. Note the control room window in the background, visible through the open access doors. (Photo credit: NASA A-27956)

HYPERSONIC HELIUM TUNNEL

This 1964 aerial view shows Building N-231, which housed the Hypersonic Helium Tunnel, and its two vacuum spheres. Note the horizontal bottle rack for storing the high-pressure helium next to the building. The compressor was in the building partially visible at left. (Photo credit: NASA A-33038-22)

SIGNIFICANCE

The Hypersonic Helium Tunnel (HHeT) was the first tunnel at Ames designed specifically to utilize helium as the test gas to generate higher Mach numbers than were practical for air in a similar tunnel. It provided researchers with a tool to evaluate the inherent advantages and disadvantages of using helium as a substitute for air in hypervelocity wind tunnels, and its success justified the construction of a second, faster helium tunnel at Ames.

DESCRIPTION

The HHeT was a hypersonic tunnel specifically designed to utilize helium as its test gas. Built in Building N-231, the HHeT was a blowdown tunnel that received helium from a 6,000-pound-per-square-inch bottle storage rack and exhausted to twin vacuum spheres. The vacuum spheres were connected to a seven-stage reciprocating compressor and gas purifier so that the helium could be reclaimed and returned to the bottle storage rack, or reservoir, which was located adjacent to Building N-231.

The HHeT circuit included a helium storage reservoir; a pebble-bed heater filled with cast-iron pebbles; four interchangeable nozzles designed for Mach numbers of 8,

15, 20, and 26; a 20-inch-diameter test section with a pitch-adjustable sting; a diffuser; and a pair of 75-foot-diameter vacuum spheres. The helium recovery compressor in Building N-229-A—originally installed to support helium operations in the 3.5-Foot Hypersonic Tunnel (3.5-Foot HyST)—pulled the gas from the spheres between runs and pumped it under pressure through a purifier system and back into the rack of storage bottles. The purifier chilled the helium with cryogenic nitrogen, which caused impurities, particularly trace gases, to condense and settle out of the helium, resulting in a 99.4 percent pure test gas. This recovery cycle took approximately 2 hours, allowing the tunnel to be run as much as two or three times during an 8-hour shift.[177]

The pebble-bed heater design resulted from earlier work by Jack Stalder at Ames to develop a reliable, high-temperature device capable of releasing stored heat to a gas flow both rapidly and with minimal flow resistance. The heater consisted of six horizontal cylinders lined with refractory brick and filled with small, cast-iron spheres. A natural gas flame heated the spheres prior to each run, and they released their heat to the test gas as it flowed through. Depending on the sphere material, temperatures of several thousand degrees could be obtained in pebble-bed heaters, but the HHeT's use of helium limited the required temperature to less than 1,000°F.[178]

Models were mounted on a sting that was supported through the test section's floor. This sting employed an electro-hydraulic actuator to adjust the pitch from –15 degrees to +30 degrees. A preprogrammed controller drove the actuator. Model access was through a side door, which could be fitted with an optically flat glass window or one curved to match the test section's wall.[179]

During operation, a throttling valve between the reservoir and heater controlled the gas flow and, hence, the stagnation pressure at the model. An automatic controller actuated it to maintain the desired set point. Starting the tunnel could, however, be problematic, particularly for flat-faced models. Operators employed two techniques to alleviate starting problems. For all runs, they prepressurized the system from the reservoir to the tunnel at a pressure somewhat higher than needed. The tunnel had a quick-acting valve just ahead of its nozzle, and when it opened, the high initial pressure quickly established the desired flow, which the stagnation pressure controller then managed. Models measuring over 1.5 inches in diameter presented another challenge because they "choked" the tunnel. To remedy the problem, engineers installed a "flow-starting spike" ahead of the model. Mounted on a vertically retracting rod, this slender, pointed spike was inserted during the start and stop portions of the run, and retracted for the data collection portion. It helped control shock formation, reduced the maximum axial stresses on the model by as much as 50 percent, and allowed blunt models of up to 3 inches in diameter to be successfully tested. A Beckman Model 210 data acquisition system accepted up to 100 channels of analog pressure, temperature, and force measurements, converted these data to a digital format, and recorded them on magnetic tape for later analysis.[180]

HISTORY

As interest in hypersonic flight and hypervelocity atmospheric reentry grew during the 1950s, researchers at the NACA's Langley and Ames laboratories pursued different concepts in their development of test facilities capable of speeds above Mach 10. Engineers and researchers at Ames largely concentrated on techniques that used air, and they built several experimental facilities, including the Low-Density Tunnel and the 6- by 6-Inch Heat-Transfer Tunnel, that used low density or high temperature to address the air liquefaction problem. Neither of these facilities proved very successful, but they did provide numerous learning experiences, and those experiences ultimately led to advances in high-temperature devices, such as pebble-bed heaters and arc-jet tunnels. Others at Ames pursued shock tubes and counterflow ballistic tunnels, using air and other gases to greater success.[181]

Langley researchers and engineers also investigated air techniques, but they also began to seriously try to use other test gases, such as nitrogen, carbon dioxide, and helium, in some specialized tunnels they included in the Gas Dynamics Laboratory (now the Hypersonic Facilities Complex), which opened in 1951. Two helium tunnels started operation in 1952, and two more opened during the 1960s.[182]

Langley researchers saw two possible advantages for helium. Firstly, the speed of sound (Mach 1) in helium is almost three times that in air at the same temperature. Secondly, helium does not liquefy until its temperature reaches –452°F, only a few degrees above absolute zero, making heating unnecessary up to about Mach 25, and reasonable heat permits speeds as high as Mach 40. Helium did, however, have its disadvantages, one being its molecular structure. At high temperatures, helium, a monatomic gas, had different thermodynamic properties than air, which is composed mostly of diatomic molecules. Researchers spent most of the decade trying to develop the corrections needed to apply helium results to air.[183]

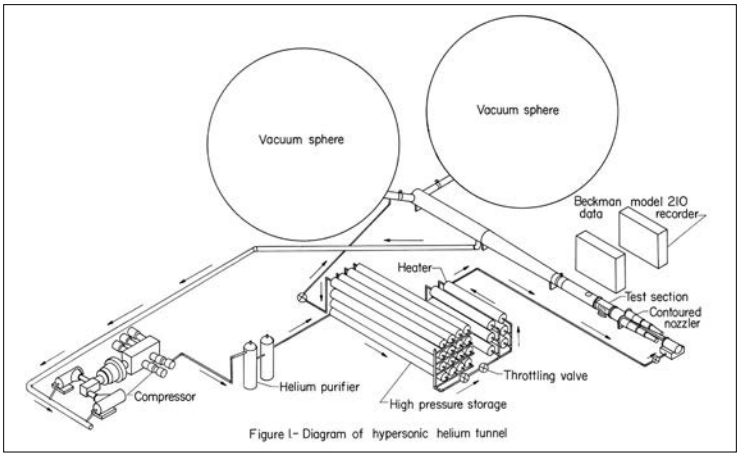
Ames engineers, particularly Glen Goodwin and Alfred Eggers, Jr., were aware of the work at Langley, and, by 1958, they had come to believe that helium tunnels might be the best practical way to test at hypervelocity speeds. Both men began designing a helium tunnel, ultimately merged their efforts, and proposed a 12-inch helium tunnel in 1959. The proposed tunnel would use four interchangeable nozzles to produce specific speeds, experience having proved that adjustable nozzles worked poorly at such high speeds, and it would make use of helium recovery equipment that already existed. The funds were approved that year, but the design went through several iterations, including size changes, before the final design for the 20-inch HHeT emerged. A 14-inch prototype erected in the 3.5-Foot HyST's building validated the design, and construction of Building N-231, the tunnel, and the two vacuum spheres proceeded rapidly. (The 14-inch tunnel remained in service for several years after the HHeT opened, but it was demolished by 1970.)[184]

The HHeT opened in 1960, just as the differences in the behavior between helium and air were finally being understood well enough that realistic corrections of helium data could usually be made. The tunnel's relative ease and low cost of operation soon resulted

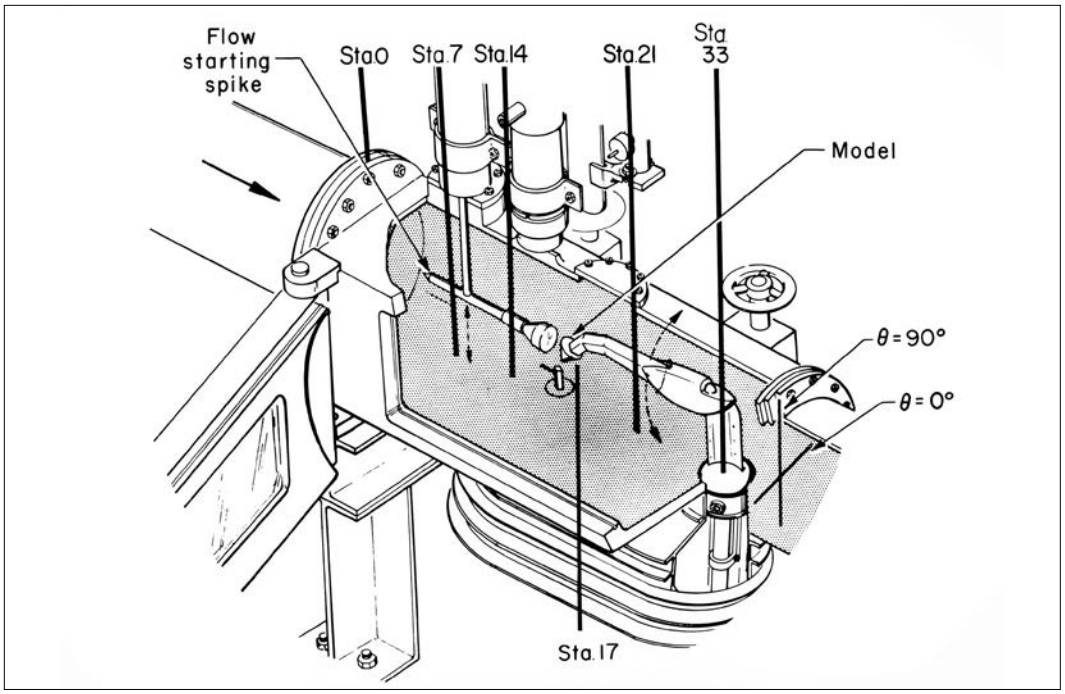
in it being booked to do preliminary testing to reduce the number of tests needed in the larger, more-expensive 3.5-Foot HyST. In spite of the corrections, however, experience in the HHeT revealed some situations where helium data could not be accurately translated into valid data for air. A situation involving a complex array of shock waves or a high ratio of skin friction to pressure drag produced data curves that did not resemble those for air. Complex mixtures of sub- and supersonic flow could be problematic as well.[185]

In spite of helium's limitations, the HHeT proved useful in studies of basic aerodynamic performance at hypersonic and hypervelocity speeds, and the tunnel hosted several test programs during the early 1960s to investigate the behavior and controllability of reentering spacecraft. One important program employed a free-flying Apollo Command Module with instruments that radioed data to a receiving antenna. A pneumatic launcher was used to launch it into both the 14-inch and 20-inch helium tunnels, and the model also saw testing in the 1-Foot Shock Tunnel. The HHeT also demonstrated that a helium tunnel with still higher speed capability for tests of probes designed for the outer planets could likely be a useful and practical addition to the Ames Center, thereby strengthening the case for the Mach 50 Helium Tunnel (M50HeT).[186]

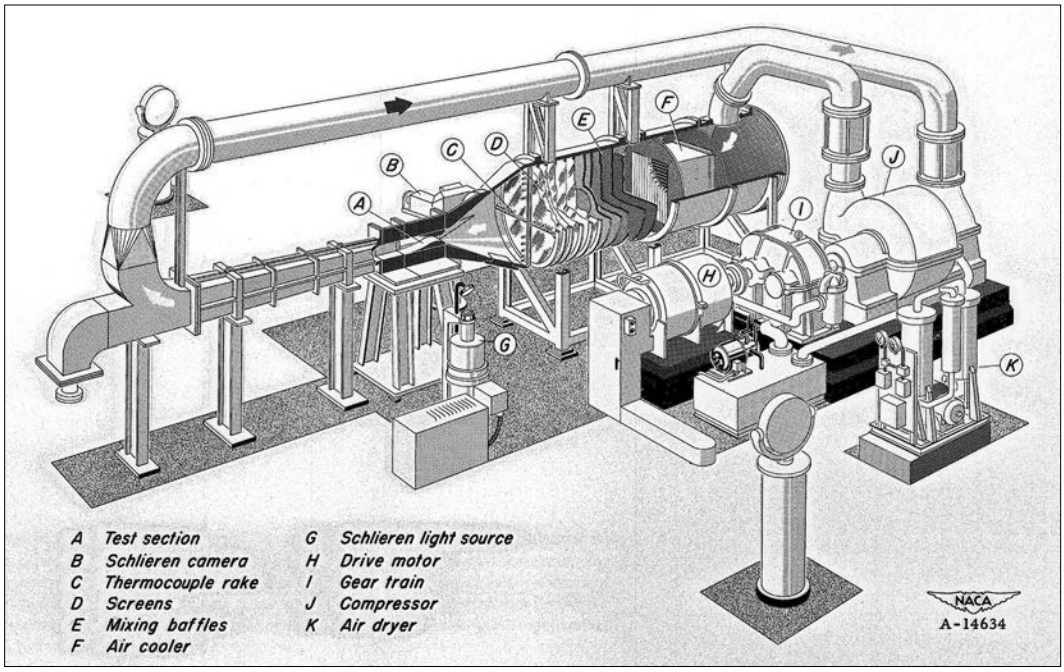
Though successful, the HHeT enjoyed only a short life. Completion of the M50HeT in 1965 did not, as expected, make the HHeT redundant, but by that time, interest in helium research had waned. During the late 1960s, the rise of computational fluid dynamics (CFD) led to the need for a facility capable of generating high enough speeds and Reynolds numbers to validate high-speed CFD code. This need produced the two High Reynolds Number Channels, which Ames management elected to install in Building N-231, where the HHeT's vacuum spheres could serve them. The HHeT's precise demolition date has been lost, but it would have to have been removed by about 1971 to avoid delaying the new installation. The twin vacuum spheres remain in place, but no portion of the HHeT inside the building is known to survive.



This diagram shows the arrangement of the Hypersonic Helium Tunnel and its helium recovery system. During a test run, the vacuum spheres captured the gas, and recovery took about 2 hours. (Image credit: NASA A-28763-2)

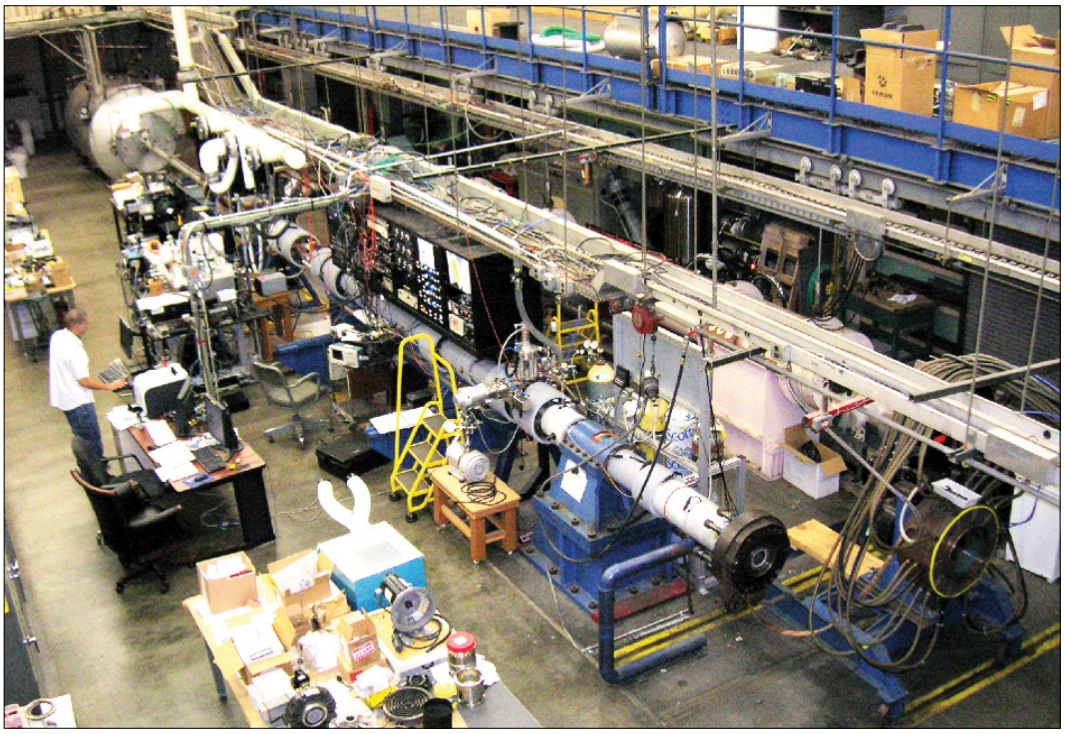


This drawing of the Hypersonic Helium Tunnel's test section shows the flow-starting spike inserted prior to a run. It was retracted after supersonic flow had been established to fully expose the model to the gas flow. (Image credit: NASA A-28763-3_1)



The 6- by 6-Inch Heat-Transfer Tunnel, seen here, and the 2- by 2-Inch Low-Density Tunnel were early attempts to generate hypersonic test conditions at Ames. Their problems led Ames engineers to consider building a helium tunnel for hypersonic and hypervelocity testing. (Image credit: NASA A-14634)

ELECTRIC ARC SHOCK TUBE



An overall view of the Electric Arc Shock Tube with the driver at lower right and the vacuum chamber at upper left. The driven, or shock, tube passes behind the electrical cabinets. Note the red flanges containing instrumentation ports. The bank of capacitors is out of sight to the right. (Photo credit: NASA)

SIGNIFICANCE

The Electric Arc Shock Tube (EAST) was the first major shock tube at Ames to use a high-energy electric arc as its prime mover. Able to achieve very high speeds and enthalpies, it has been the venue for a variety of radiation, ionization, and chemical-reaction investigations associated with high-energy gas flows, including simulations of entry into the atmospheres of the outer planets.

DESCRIPTION

The EAST, constructed in Building N-229, the structure originally built to house the 3.5-Foot Hypersonic Tunnel, is a high enthalpy shock tunnel designed to produce test speeds between roughly Mach 9 and Mach 60+ and enthalpies as high as 15,000 British thermal units per pound of test gas. Like many light-gas guns, the EAST uses helium as its driver gas, but the desired speed range made combustion heating impractical, so an arc driver powered by a 1.25-megajoule, 20/40-kilovolt capacitor bank capable of discharging its energy in 100 microseconds was designed and built.[187]

The EAST consists of a capacitor bank; arc-discharge chamber and driver tube; shock, or driven, tube; nozzle; test section; and vacuum tank. While it is designed to

tighter tolerances and generally operates at higher enthalpies than combustion-driven shock tubes, the EAST operates like other shock tubes after the driver gas has been heated. A primary shock wave moves through the test gas in the shock tube until it reaches the end and is reflected toward the driver tube. On the return, this shock meets and retards the forward-moving gas, thereby compressing it non-isentropically to a high pressure, temperature, and, hence, enthalpy as it passes through. When the primary shock wave reaches the end of the shock tube, it also ruptures a thin plastic diaphragm, which allows the highly compressed test gas to flow through an axisymmetric nozzle, where it expands and accelerates, and then passes through the test section and into a 300-cubic-foot cylindrical vacuum tank.

The EAST is distinguished primarily by its capacitor-discharge arc driver. The capacitor bank consists of 180 units, each rated at 27.5 microfarads and 20 kilovolts. These are connected in 18 series-pair groups, allowing operation at potentials of up to either 20 or 40 kilovolts to suit the test and facility setup. The current is conveyed in 10 coaxial cables from the capacitor bank to a collector assembly on the driver, and thence to a hollow electrode centered in one end of a 10-foot-long driver tube. At the other, discharge, end is a ground electrode and stainless steel primary diaphragm machined to rupture at a precise pressure. A thin trigger wire connected to the ground electrode lies inside the driver tube until actuation. It is connected to an insulating cotton thread that passes through the hollow electrode to the plunger of a pneumatic cylinder. With the system energized, admitting air to the cylinder causes it to retract, pulling the thread and trigger wire taut, where the proximity of the trigger wire to the electrode initiates a high-energy arc for approximately 100 microseconds. The almost-instantly heated and pressurized helium driver gas ruptures the primary diaphragm and starts the primary shock moving down the driven tube.

While the secondary diaphragm, nozzle, and test section are similar to those of the Hypervelocity Shock Tunnel, their proportions are different to suit the EAST's performance, and the test section has a hexagonal cross section that transitions into a 30-inch-diameter, 18-inch-long exit to the vacuum cylinder approximately 10 feet long and 6 feet in diameter.

While this description of the EAST generally applies, the facility can be set up in several configurations for different test protocols. Five separate driver tubes are available to furnish different energy levels. Either a 24-inch-diameter shock tube or the original 4-inch-diameter shock tube can be used with these drivers, and the 4-inch shock tube also can be used to drive a 30-inch-diameter secondary driven tube that Ames curiously calls a "shock tunnel."[188] The driven tube is sectional so that its length can be optimized to suit the driver volume and the particular test gas, which can be dry air, gases such as argon and carbon dioxide, or custom mixtures. The commonly used lengths are between approximately 24 and 50 feet. The exit of the EAST's driver is rigidly secured to the floor to transmit thrust forces, but the remaining portions of the device are sectional

and movable to permit their assembly into the various configurations, where they are bolted together. The heavier components roll on rails.

Models are sting-mounted in the test section, and the sting mount contains a spring-mounted lead mass to partially dampen accelerations. Since test times with stable flow are on the order of 1.5–2.0 milliseconds, and the internal pressure transducers mounted in the model tend to be both temperature- and pressure-sensitive, any dampening of the start-up effects has a positive effect. Adjustable counterweights on the rear of the sting allow the model's weight to be precisely balanced and the model properly aligned with the airflow. To further reduce acceleration effects, a sealed slip joint isolates the test section from some of the longitudinal movement of the tube and nozzle.

Models are typically instrumented for temperature or pressure, though their small sizes make concurrent measurements of both impractical. Quartz-crystal piezoelectric and variable-capacitance pressure transducers are used, and thermocouples are employed with both thin-wall and thin-film techniques. Their analog signals are converted into digital data and recorded by a computerized data acquisition system that can record 500,000 samples per second. To minimize electrical noise from the ignition arc, an automatic circuit isolates the instruments, as well as the probes and timers used to determine shock position and velocity, until the arc discharge has ended.[189]

HISTORY

As discussed in the listings on the Hypervelocity Shock Tunnel and Hypervelocity Free-Flight Facility, shock tunnel development began at Ames in the 1950s and continued to advance the technology during the 1960s. The increasing feasibility of deep-space probes to the large outer planets with deep atmospheres, where entry speeds would easily exceed Mach 50, prompted engineers and researchers at Ames to investigate techniques for increasing the speed capability of shock tunnels and tubes to that Mach number or higher.

Hypervelocity, high-temperature, chemically reacting gasdynamics was, and still is, a highly complex discipline, and by the late 1960s more progress had come through theoretical analysis than empirical methods. Practical experimental facilities were few, and their small size and millisecond run times produced data that often only inferred the values for parameters of interest, making significant post-test processing of the data necessary. At best, the extremely short run times raised questions about data stability and repeatability, and it was difficult for researchers to accurately know how closely any empirical and theoretical data *could* agree. Models were necessarily small, and they did not have sufficient room to accommodate both temperature and pressure transducers, so separate models were required. Their small sizes made even minor fabrication differences very significant.

The challenges of building a better, faster shock tube were substantial as well. They included the development of smaller, faster-responding instruments; a driver with higher energy that could deliver it to the driver gas in a quicker, more-uniform manner; and

the design of a facility that could deliver both high Mach numbers and high enthalpies. High Mach numbers usually require gas expansion through a supersonic nozzle, which cools and depressurizes the gas. The trade-off is a lower enthalpy, the term representing the total energy present in the gas. Other practical considerations, such as heat loss to the surroundings, further complicated the problem.

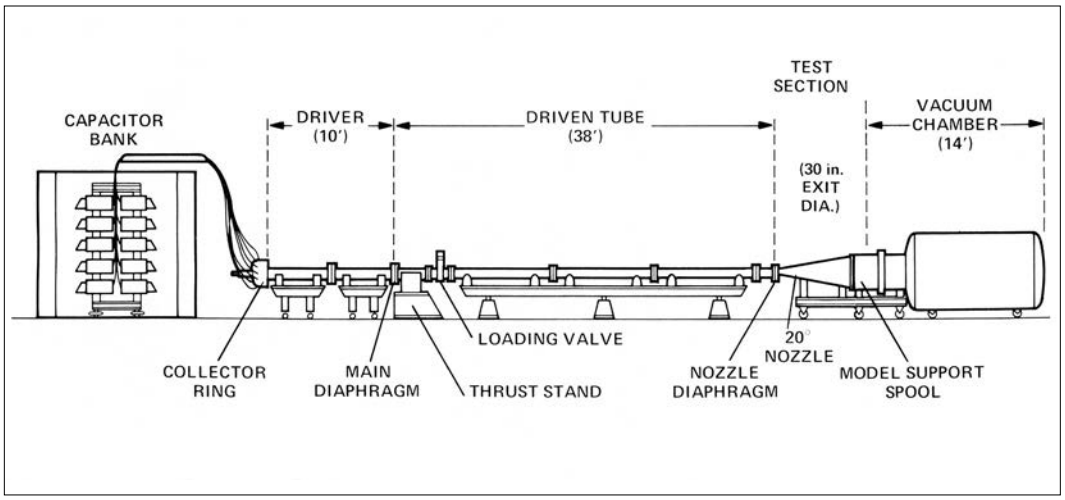
Ames engineers took on this complicated challenge. Examining the recent work in hypervelocity simulation, they realized that achieving actual flight velocities was crucial to generating the proper flow fields of reacting gases around the test body, which mandated rather large expansions through a nozzle. But flight-level enthalpies were also necessary for the reactions to occur, meaning that the gas entering the nozzle had to be very hot and under a high pressure. Work with other reflected-shock facilities convinced them that this type of tunnel offered the greatest chance of success in generating the hot, high-pressure test gas needed.[190]

Early arc-driven shock tubes were implemented at GE Space Systems Labs, at AVCO-Everett research laboratories, and at Ames in building N230.[191] The engineers became convinced that an electric arc through a sealed chamber filled with a light driver gas, such as helium, would be the best way to heat that gas intensely and uniformly. A capacitance-discharge circuit could transfer as much as 1 megajoule (948 British thermal units) of energy to the helium in about 100 microseconds, and the circuit could be adjusted as needed to reduce the energy or change the discharge time. That permitted the control, or "tailoring," of the conditions at the driver gas–driven gas interface and to obtain a range of performance in the tunnel. The driver was 4 inches in diameter and nominally 10 feet long, though inserts could shorten it when desired. It could heat the helium to 7,100°F and raise its pressure to between 3,500 and 10,800 psi. This produced stream enthalpies of up to almost 12,500 British thermal units per pound of dry air, well above what other NASA facilities could achieve.[192]

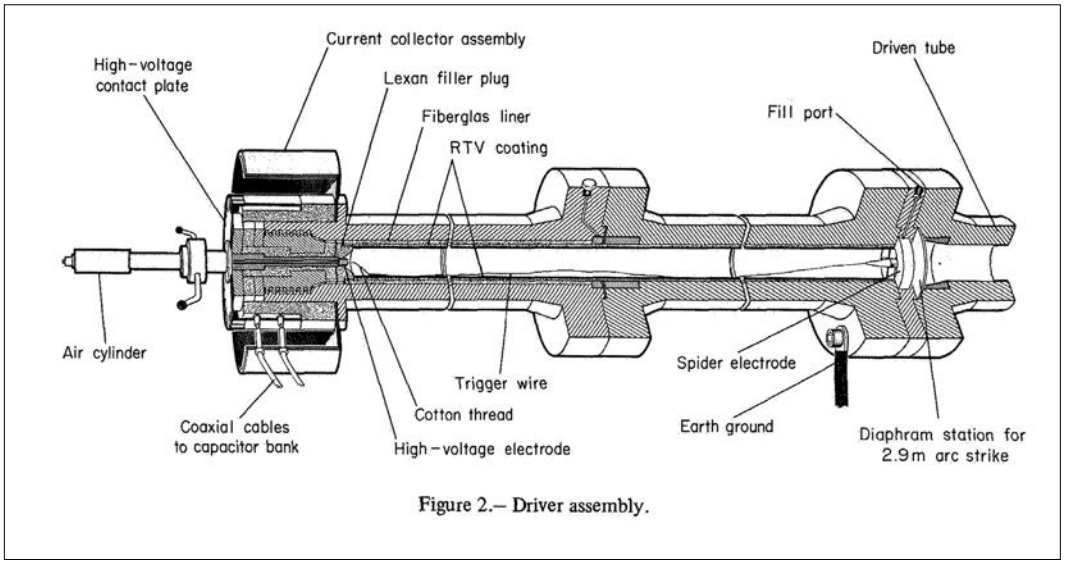
The EAST was erected in an available space in Building N-229, and it opened in 1965. Except for the electric-arc driver, the tunnel functions like other reflected-shock tunnels, but with its higher energy level, it can produce the higher speeds and enthalpies the engineers sought. It can use any desired test gas, with the charge pressures of the driver and driven gases closely controlled. Dry air, carbon dioxide, argon, hydrogen, and likely other test gases have been utilized, since they yield a wide range of test section speeds. For example, air initially at a pressure of 1 Torr (0.019 pound per square inch absolute) can be accelerated up to approximately 51,500 miles per hour, while hydrogen under the same initial conditions can reach almost 103,000 miles per hour. Most tests are run at considerably slower speeds and higher initial pressures.

The EAST has received several instrumentation upgrades during its life, as well as additional drivers, shock tube components, and a 25 percent increase in capacitance to enhance its usefulness. The original reflected shock tunnel has been converted to a shock tube for incident shock studies, with the old test cabin being mothballed and the exit being converted to an optional (nonreflecting) expansion cone for studies of expanding

flows. The 4-inch tube was rebuilt from aluminum in 1989 and the 24-inch tube replaced with the aluminum 21.3-inch-diameter Low Density Shock Tube (LDST) in 2023. The EAST remains in service as NASA's premier facility for high-energy gasdynamics studies and has been used to reconstruct entries to Mars and Earth return in addition to informing proposed planetary probe missions.[193]

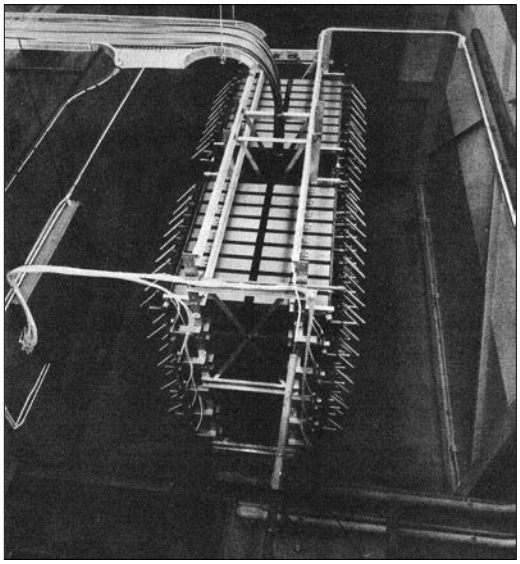


This drawing shows the major components and general arrangement of the Electric Arc Shock Tube, which can achieve test speeds of over Mach 60 in air. This is one of several possible configurations that can be employed for various test programs. (Image credit: NASA A06-0157-003)

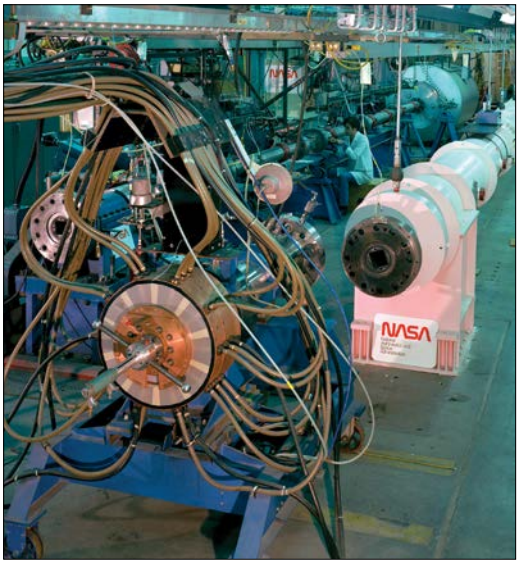


The Electric Arc Shock Tube's driver, shown in this cutaway drawing, uses energy stored in the capacitor bank to produce an intense electric arc. The potential across the electrodes is a maximum of 40,000 volts. The air cylinder pulls the trigger wire close to the high-voltage electrode to initiate the arc, which extends between it and the ground (spider) electrode for about 100 microseconds, heating the helium in the chamber to as much as 7,100°F. The resultant pressure ruptures the diaphragm and starts a shock wave moving through the gas in the driven tube. (Image credit: NASA TM X-2814, Fig. 2)

A winged reentry vehicle model sting-mounted in the Electric Arc Shock Tube's test section in 1970. Flow is from right to left. (Photo credit: NASA A70-5700)



This 1.25-megajoule bank of capacitors furnishes the burst of energy needed to generate the arc in the Electric Arc Shock Tube's driver. (Photo credit: NASA TM X-2814, Fig. 1)



The power cables, collector assembly, and pneumatic cylinder are clearly visible in this 1978 view of the Electric Arc Shock Tube's driver, which has been rolled away from the rest of the device in the background. (Photo credit: NASA AC78-1071)

MACH 50 HELIUM TUNNEL

This 1964 aerial view shows Building N-238, which housed the M-50 Helium Tunnel and several other facilities. The array of large ducts at right is part of a steam ejector system that evacuates newer facilities in N-238 and another building out of sight to the right. (Photo credit: NASA A-33038-22b)

SIGNIFICANCE

The Mach 50 Helium Tunnel (M50HeT) was the second helium tunnel at Ames, and it was the largest and fastest tunnel at Ames to use helium as the test gas. Its intended service was the investigation of planetary atmosphere entry at speeds of up to Mach 50 and Reynolds numbers of approximately 1 million per foot, but the tunnel experienced serious technical problems and failed to perform as expected.

DESCRIPTION

The M50HeT was a hypervelocity tunnel specifically designed to utilize helium as its test gas. Built in one bay of Building N-238, the M50HeT was a blowdown tunnel that received helium from a 15,000-pound-per-square-inch bottle storage rack and exhausted it to a steam ejector evacuation system it shared with several arc-jet facilities in Buildings N-238 and N-234. The helium was recovered from the steam ejector system, purified, and compressed for future use. The steam ejector could continuously maintain 0.05-pound-per-square-inch absolute pressure at the tunnel's exhaust.[194]

The M50HeT consisted of a helium storage and supply system, an electric heater, two interchangeable nozzles, an open test section within a sealed test cabin, a diffuser, an isolation valve, and a connection to the steam ejector system. These components were

fabricated primarily from steel, with stainless steel used for critical nozzle elements. The two nozzles were designed for nominal speeds of Mach 40 and Mach 50, and the heater could supply the gas at temperatures as high as 1,500°F to prevent liquefaction. The supply system's pressure controller could be set to deliver helium to the nozzle at any pressure between 1,000 and 10,000 psi, with 1,500–2,000 psi being the normal operating range. A manual control option was available, but the automatic system effectively maintained the stagnation pressure within ±0.5 percent, and it was generally used. The storage reservoir contained enough helium for run times of up to 20 minutes. Typically, up to 1 minute was needed to establish the desired test conditions before data recording began.

The M50HeT utilized an electric resistance heater instead of the pebble bed type used in many other hypersonic tunnels. Measuring 14 feet, 7.5 inches long by 1 foot, 5.5 inches in diameter overall, the heater contained 36 Inconel-600 tubular elements mounted in parallel, each one $^{5}/_{16}$ inch in diameter by 11 feet, 5⅛ inches long. The incoming gas passed from one end of the heater to the other and back through two annular passages before it entered the heating elements. This arrangement cooled the heater shell while preheating the gas. Gas exited the heater directly into the nozzle's throat, which was also heated.

The two axisymmetric nozzles were designed for nominal speeds of Mach 40 and Mach 50, but they were intentionally terminated somewhat short of their theoretically complete expansion to minimize the thickness of the boundary layer. The bulk of the nozzle, which extended into the test cabin, was the same for both speeds. Only the 15-inch-long throat portion needed to be changed. Both throats were fabricated from stainless steel, and they included heating coils to reduce heat transfer from the gas and minimize thermal expansion and stress during the run. The nozzle's discharge into the test section measured $28^{13}/_{32}$ inches in diameter. This produced a uniform core flow approximately 4 inches in diameter through the test section. An annular injection system around the nozzle outlet injected helium at about Mach 20 to help stabilize the open jet's boundary layer and prevent disturbances around the model from affecting the upstream flow conditions.

The test cabin and section's arrangement with an open test section in a larger sealed chamber made the M50HeT a hypervelocity version of an Eiffel tunnel. The cabin measured 10 feet on each side, and it was equipped with a sealed personnel door on one side plus a circular roof hatch. The roof hatch and each side had 1-foot-diameter windows for observation, and the floor featured a small hatch that could be fitted with a fourth observation window when needed. The original diffuser was a converging-diverging design with a 32-inch-diameter inlet that reduced approximately 2 inches before flaring to the exhaust duct's diameter of 48 inches. The diverging portion was later replaced with an 8-foot-long section of 30-inch-diameter duct with no flare at its end. The diffuser could be adjusted longitudinally to set the length of the open-jet test section between 6 and 26 inches.

Outside the building's north wall, a remotely operated valve opened during runs to connect the M50HeT to a five-stage steam ejector system that furnished a continuous vacuum for this tunnel and several other facilities located in two buildings. While it could operate continuously, using steam from a dedicated boiler, only one facility could operate at a time, making schedule coordination essential. A separation and purification system removed the steam and trace gases from the helium. A compressor then returned the helium to its storage bottles for future use.

Models were sting-supported on a hydraulically actuated mounting assembly. Mounted on a test cabin wall, this system supported longitudinal, vertical, and pitch (angle of attack) adjustments. The vertical drive was primarily used for inserting the model into the gas stream after the flow had been stabilized and retracting it at the end of the run, which it could perform in approximately 0.7 seconds. Seventeen inches of longitudinal motion were available, and pitch could be adjusted from +45 to –15 degrees. These functions were all remotely controlled from outside the test cabin, either manually or by a preprogrammed controller.

A Beckman Model 210 data acquisition system accepted up to 100 channels of analog input, converted these data to a digital format, and recorded them on magnetic tape for later analysis. Parameters typically measured during M50HeT tests included forces and moments, pressure distributions, heat transfers, and flow-field conditions.

HISTORY

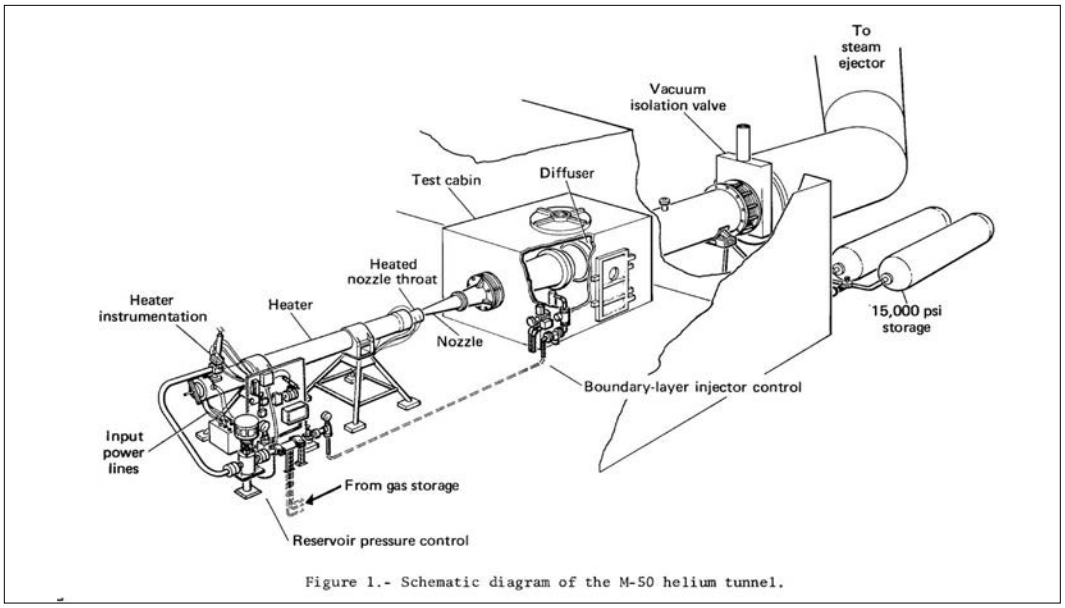
During the early 1960s, the successful operation of the Hypersonic Helium Tunnel (HHeT) at speeds of up to Mach 26 encouraged engineers at Ames to think about extrapolating the concept into a helium tunnel capable of producing speeds comparable to those that space probes would experience upon entry into the atmospheres of the outer gas planets like Jupiter and Saturn. The huge mass of these giant planets meant that any craft launched from Earth would reach speeds of at least Mach 40 when they encountered their atmospheres, and a spacecraft returning to Earth from a Jovian flyby would approach Earth at about the same speed. Facilities that could investigate the thermodynamic effects, such as arc jets, were coming online, but such speeds generated aerodynamic questions that required more than a few milliseconds to experimentally investigate. No conventional NASA tunnel operated above Mach 26, and they were limited to run times of less than about 30 seconds, too little time to adequately simulate the effects of large planet entry.

Joseph H. Kemp, Jr., and a small team of engineers developed the design for what became the M50HeT by discarding the traditional vacuum spheres that normally captured the exhaust of tunnels like the HHeT, since vacuum capacity determined their maximum run times. They chose instead to connect the new tunnel to an elaborate steam ejector system recently built to serve several arc jet facilities in two buildings. This system could maintain an absolute pressure on the tunnel's exhaust of about 0.05 pound per square inch for a virtually unlimited period. This made the helium storage capacity

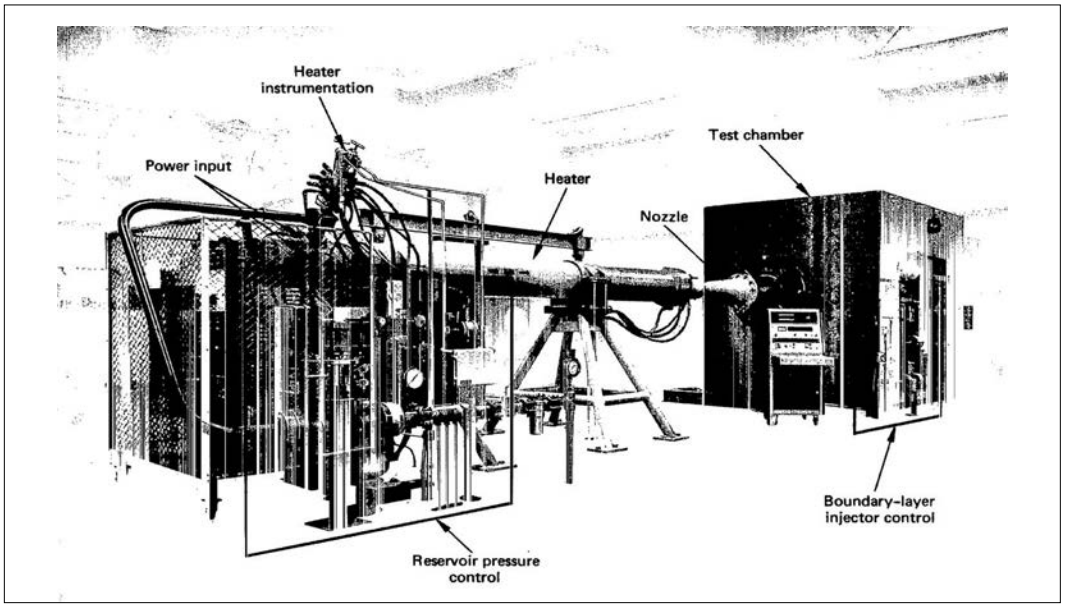
the limiting factor, but storage to accommodate the amount needed for 20 minutes of running was feasible. Even with helium's low liquefaction temperature of –452°F, heating would be necessary for speeds of Mach 40–50, but, again, Kemp departed from existing designs and chose to use an electric resistance heater instead of a pebble-bed type, since the temperature required fell within the capability of the more-conventional device. After deciding to build nozzles for Mach 40 and 50, the team designed them using a numerical method developed by Ames researchers Harry Bailey, Harvard Lomax, and Robert McKenzie.[195]

Kemp sold the design to NASA management, and Congress approved $1.5 million for its construction. Construction proceeded rapidly, and the M50HeT began operation in 1965. The tunnel operated reasonably well with the Mach 40 nozzle, actually reaching speeds as high as Mach 45, but the Mach 50 nozzle immediately experienced serious problems. Flow measurements for both nozzles varied from predictions, particularly those involving the boundary layer, which was somewhat thinner than predicted. Accordingly, both nozzles produced higher speeds than intended. This was not a serious problem with the Mach 40 nozzle, although it required an inlet pressure lower than intended for stable operation, but the Mach 50 nozzle could not produce repeatable results at all. In fact, the flow field pressure distribution seemed to worsen with each run. An investigation revealed that, even with the nozzle heater, the higher-than-expected speed had induced thermal stresses in the nozzle high enough to cause plastic deformation. In seven runs, its throat diameter had changed by almost 5 percent (0.143 inch to 0.136 inch). The Mach 50 nozzle was never again used. The diffuser was reconfigured from a converging-diverging design to one without a diverging section at some point, but available documentation does not indicate why, or whether it resulted in any performance improvement.[196]

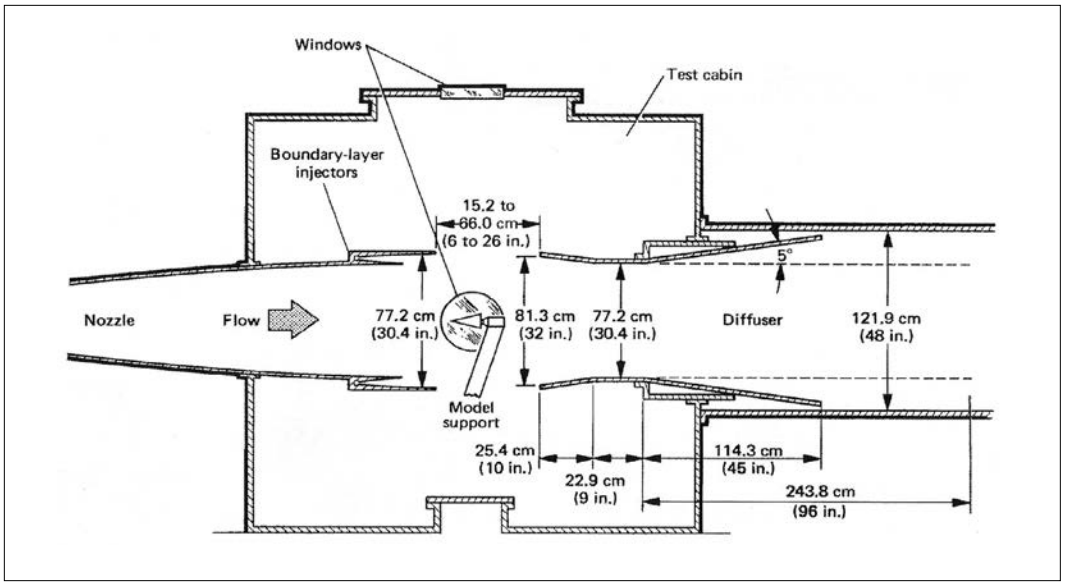
The M50HeT was a disappointment, to say the least, and its timing could hardly have been worse. Even before its completion, work in the HHeT and elsewhere had exploited most of the perceived advantages of helium in hypersonic and hypervelocity aerodynamics, and the tunnel's performance failed to deliver additional results of significance. During the mid- to late 1960s, more useful data were being generated in counterflow tunnels and arc jets, thus negating the usefulness of the M50HeT's 20-minute run time. With little usage, other projects that could make better use of Building N-238's unique services clamored for the space it occupied, and the M50HeT was demolished in 1970. No portion of it is known to survive.



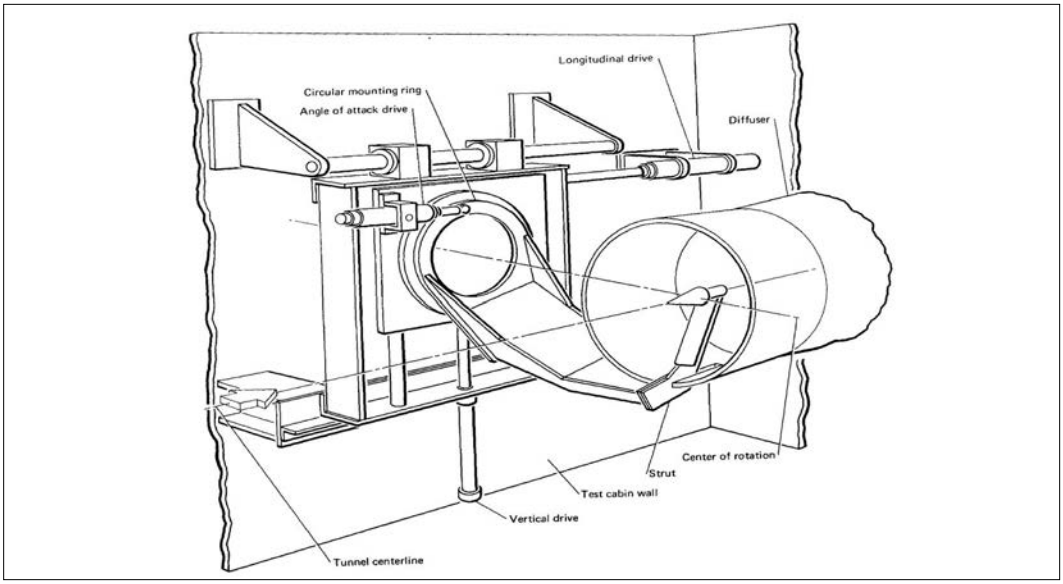
This cutaway drawing identifies the major components of the Mach 50 Helium Tunnel. (Image credit: NASA TN D-5788, Fig. 1)



All of the M-50 Helium Tunnel except for its gas storage bottles and connection to the steam ejector system is visible here. The open test section was inside the test cabin. (Image credit: NASA TN D-5788, Fig. 2)



The Mach-50 Helium Tunnel's test cabin housed its open test section. The diffuser translated to vary the opening between 6 and 26 inches, and the annular boundary layer injection helped to stabilize the flow. The dashed line represents a reconfiguration of the diffuser. (Image credit: NASA TN D-5788, Fig. 5)



The Mach-50 Helium Tunnel's hydraulically actuated model support system, mounted on a test cabin wall, permitted longitudinal, vertical, and angle-of-attack adjustments. (Image credit: NASA TN D-5788, Fig. 8)

HIGH REYNOLDS NUMBER FACILITY

High Reynolds Number Channel No. 2. The flow is from left to right. Note the open hatch at right for test section access. (Photo credit: NASA AC80-0512-3_1)

SIGNIFICANCE

The High Reynolds Number Facility (HRF) was NASA's first facility built for the express purpose of providing experimental support for the development and validation of computational fluid dynamics (CFD) code.

DESCRIPTION

The HRF consists of a pair of blowdown tunnels, known as the High Reynolds Number Channel Number 1 (HRC1) and the High Reynolds Number Channel Number 2 (HRC2), located in Building N-231. Though each tunnel has unique features and capabilities, the two tunnels share similarities in design and operation. Both are heavy-gage steel cylinders with frustums at both ends that were designed for pressures of up to 11 atmospheres (162 psia). A large pressure-relief pipe equipped with a rupture disc runs directly from each tunnel through the roof to protect the tunnel and personnel from excessive pressure. These tunnels are no longer in service, but intact.

Though only one tunnel could operate at a time, both received compressed air from compressors in an adjacent building via storage tanks with a total volume of 33,000 cubic feet at 3,000 pounds per square inch. This air entered the building through a pressure-reducing station, which decreased the pressure to approximately 200 psi and delivered it to a manifold on the south side of Building N-231's laboratory area. A control valve for each tunnel routed air from the manifold to its respective tunnel, where it entered at 100–160 psi. After flowing north through either HRC1 or HRC2, the air passed through exhaust ducts that penetrated the north wall, where valves

routed it to the atmosphere or vacuum spheres, as selected by the operator. The usable test times varied widely—from 30 seconds to 30 minutes—depending on the tunnel and test conditions. This air system is the same system originally built to support the 3.5-Foot Hypersonic Tunnel and augmented in 1975 by the Ames Underground Air Storage Facility.[197]

In either tunnel, inlet air entered a small, cylindrical chamber through a pipe that had multiple rows of radial holes through its wall but was plugged on the end. This prevented a narrow jet of air from shooting down the tunnel's centerline by directing multiple jets perpendicular to the centerline. Air exited the chamber through a perforated plate and passed into the settling chamber. For equipment and personnel safety, each tunnel was equipped with an emergency vent through the building's roof that incorporated a rupture disc designed to open at 200 pounds per square inch.

HRC1, the smaller of the two tunnels, has a maximum inside diameter of 7 feet. Its length varies, depending on which of three interchangeable test sections is mounted, but the fixed portion containing the inlet, screens, and entrance cone measures 25 feet long. Two of the test sections have rectangular cross sections measuring 10 inches wide by 15 inches high by 5 feet long. One of these was used for subsonic tests between Mach 0.4 and 0.9, while the other could be fitted with nozzles that produced Mach 2.0 or 3.0. The third test section is 9.5 inches in diameter by 8 feet, 10 inches long, and it could be fitted with nozzles for Mach 1.5, 2.0, or 2.5.

The HRC1's settling chamber expands from approximately 2 feet, 6 inches to 7 feet in diameter, and it contains seven flow-straightening screens of 2, 4, 8, and 16 mesh. The emergency vent connects to the cylindrical portion of the settling chamber. The downstream frustum contains the entrance cone and a transition section that formed a portion of the specific nozzle selected. The selected test section, including the remainder of the nozzle, bolts to the transition section, and a section of pipe connects the test section exit to the exhaust manifold.

The larger HRC2 has a maximum inside diameter of 8 feet and an overall length of approximately 36 feet, not including inlet and exhaust piping. Its settling chamber expands from 3 feet in diameter at its inlet to 8 feet, with the frustum portion holding two additional perforated plates. Flow-straightening screens (18 mesh) are mounted in the first portion of the cylindrical settling chamber, which also has space for additional acoustic and honeycomb devices. The emergency overpressure vent connects to this portion of the tunnel. The HRC2 ran at a maximum pressure of 7 atmospheres (103 psia), with a speed range of Mach 0.6–0.8.

A contraction cone and nozzle lead to the test section, which measures 24 inches high by 16 inches wide by 9 feet, 2 inches long. These components are contained within a cylindrical plenum—sometimes called a "test cabin"—that externally appears to be an extension of the settling chamber. Two rectangular hatches with radiused corners provide access to the test cabin, where smaller hatches open for test section access. Two remotely operated flaps at the test section's exit were used to control the Mach number.

Immediately downstream, the diffuser penetrates a bolted end cap and connects to the exhaust manifold.

Since it is inside a plenum that serves as the pressure vessel, the test section was fabricated of lighter-gage steel. The top and bottom walls of the test section have flexible walls that can be contoured using seven jacks each. This adjustment allows the wall shape to be changed to minimize wall-interference effects throughout the Mach number range. The sidewalls each have two porous panels for boundary layer removal ahead of the model's location with flow through them induced by a vacuum and controlled by a throttling valve. The contours for the flexible walls were calculated and set to accommodate the change of mass resulting from boundary layer removal and, thus, match the resulting streamline. Circular windows in each sidewall also serve as the model mounts. Almost all models tested were airfoils that fully spanned the test section, and rotating these windows changed the model's pitch. These were not dynamic adjustments, so operators set all of them prior to each test run. A vent near the exit equalized pressures in the test section and plenum.

These tunnels shared a computerized data acquisition system and much of their instrumentation. The airfoil models were made with pressure ports and passages to one end for connection to pressure transducers.

HISTORY

During the 1960s, rapid advances in computer technology and capabilities gave engineers and researchers computational tools that allowed them to begin developing software to perform highly complex and laborious mathematical analysis that had previously been impractical to do. One of the most challenging, and potentially rewarding, fields for this was aerodynamics, a specialty within the broader field of compressible fluid mechanics, and aeronautical researchers were among the first to start investigating how the complex airflow around aircraft might be modeled. In addition to their knowledge of aerodynamic parameters and theory, they were well aware of the capabilities and limitations of wind tunnels. With this background, they began writing computer code for what became known as computational fluid dynamics (CFD).

By the 1970s, results appeared promising, but the programmers realized that they needed methods to accurately validate their calculations, and that they needed much more information about the nature and effects of turbulent flow fields. Some experiments could be run in NASA's existing wind tunnels, but they really needed a wind tunnel dedicated to CFD development and validation. At the time, almost no wind tunnel data existed that accurately described an airfoil's performance that did not include some "correction" for wall interference. Typically, an empirically derived adjustment was made to Mach number or angle of attack that compensated for the interference. This was a practical solution for empirical testing, but such corrections obscured potential problems with CFD code.[198]

In response, a team of engineers at Ames led by John B. McDevitt and Thomas E. Polek specified and acquired a small blowdown tunnel for two-dimensional airfoil testing at very high Reynolds numbers. High pressure was a well-known technique for high Reynolds numbers in a wind tunnel, and Ames could furnish that easily. A high-pressure air and vacuum system built for the 3.5-Foot Hypersonic Tunnel could furnish abundant dry air at up to 200 psi and a high vacuum. Conveniently, space for the tunnel existed in a building next to the storage and vacuum tanks. Making the test section two-dimensional minimized wall interference from the sidewalls. The team developed a design that had a fixed cylinder with tapered ends that contained several flow-conditioning devices and the contraction cone portion of the nozzle. To provide several speeds, they made three interchangeable test section portions that bolted onto the end of the fixed portion. They paid particular care to the contraction cone's design to make sure it delivered air to the test section with no vena contracta to ensure low turbulence along the test section's walls. Each test section was built with its top and bottom walls contoured to match the predicted streamlines that would have existed had no wall been in place. Inserts or a translating wedge allowed operators to trim the test speed as necessary for repeatability. While tunnel design and construction proceeded, other Ames researchers developed a simple, standard airfoil for their initial tests.[199]

While managers at Ames supported the development of CFD methods, the young field was less well known in places like Washington, DC. To minimize the tunnel's visibility and difficult questions about its purpose, Ames decided to not to call it a wind tunnel, but rather to name it the High Reynolds Number Channel, and that name has remained. The HRC1 began operation in 1973, and researchers immediately began a thorough study of its flow characteristics, beginning with the subsonic test section. They employed surface pressure measurement, oil-film studies, and shadowgraph imaging of flows up to Mach 0.71 and Reynolds numbers up to 17 million. The data were useful for basic CFD development, but the validation studies, supplemented by continuing measurements of flow quality, identified some discrepancies and indicated that further refinements would be desirable. One particular concern was the possibility of some transverse flows across the airfoil that could degrade the data.[200]

To support Space Shuttle exhaust plume studies, Ames completed the high-volume Underground Air Storage Facility in 1975. With the additional capacity provided by this new air storage facility, McDevitt and his team saw an opportunity to install a second high Reynolds number channel with features to address the HRC1's shortcomings. The design for the HRC2, though based heavily on that of the HRC1, incorporated a completely revised test section. As with the HRC1, the initial concept was to use interchangeable test sections that optimized the geometry for each test condition, but this evolved into a test section with flexible top and bottom walls. This could be done because the engineers enclosed the test section within a cylindrical plenum, initially termed a "test cabin," that served as the pressure vessel, thus allowing the test section walls to be thin. A pair of vents ensured that the plenum and test section would remain

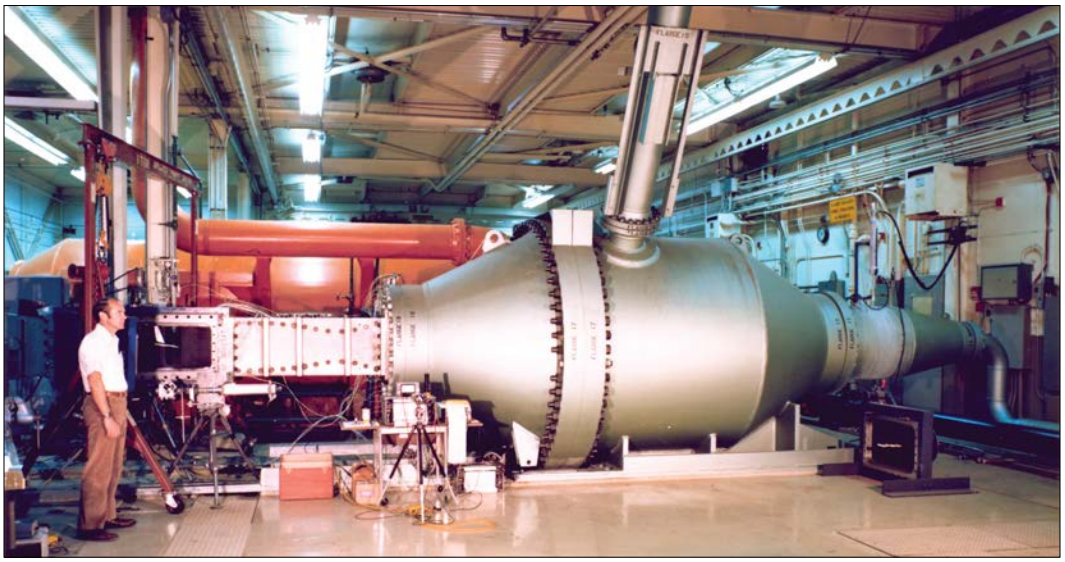
at the same pressure. The two flexible walls each received a set of seven jacks that operators could use to set the desired contour for different conditions. They calculated each contour to match the streamlines that would exist without any barrier in place. To minimize the possibility of transverse flow and sidewall interference, the team added a boundary layer removal system with two sets of porous, sintered stainless steel panels—one near the entrance and one near the model on each side—with each pair independently controlled. The exhaust vacuum sphere furnished the suction. As in the HRC1, the airfoil model was mounted between the sidewalls, but the HRC2 included vertical turntables in the mounting structure to allow the angle of attack to be varied, as researchers anticipated the use of multiple airfoils at various angles of attack as CFD code became more capable.[201]

As soon as the HRC2 was completed in 1980, McDevitt and his team began an extensive, methodical calibration of the tunnel, beginning with its boundary layer removal system and adding complexity only after they understood the performance at each level. Ultimately, some boundary layer corrections still proved necessary to correct for sidewall interference, but they were minor and predictable. The flexible top and bottom walls performed as planned, and "very good agreement was obtained between experiment and predicted values for the model in free air."[202]

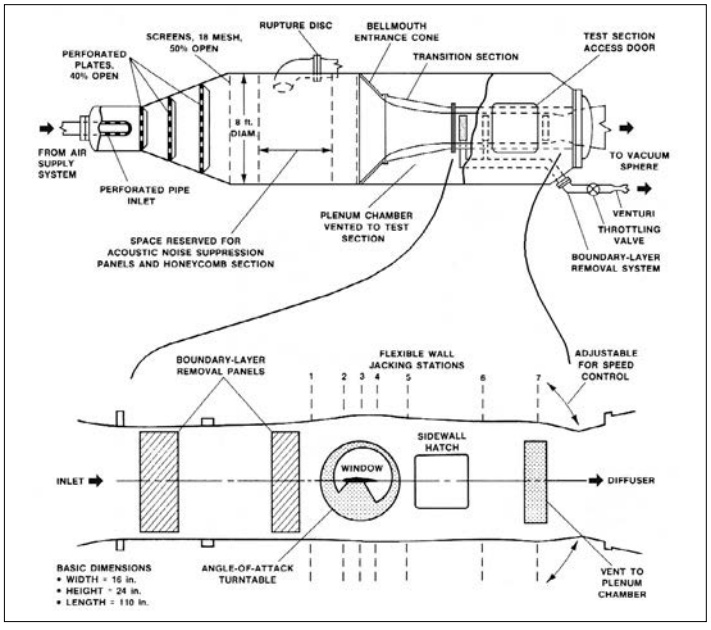
Research work in the HRC2 began with an extensive set of tests to measure and document the steady and unsteady flow fields around a few well-known airfoils. The primary measurements taken were pressures along the airfoil and elsewhere in the test section, supplemented by hot-wire anemometry. Following checks against other known information about these airfoils, these data became the standard for CFD code validation at Ames.

While the development of CFD validation data justified the installations of HRC1 and HRC2, this program's objectives were accomplished in a fairly short time. As is often the case, researchers soon realized that the tunnel could be useful in other ways as well, especially for basic research that was difficult to schedule and expensive to do in Ames's larger tunnels. Laser Doppler velocimetry (LDV), a flow-visualization technique using laser light to illuminate minute particles in the airstream to measure localized velocities, complemented the HRC1 and HRC2 studies well, and H. Lee Seegmiller began investigating ways to improve it. Spherical polystyrene latex particles in an aqueous suspension were known to work well, but the technique had problems with the carrier not fully evaporating. Using the two HRCs and two additional pilot tunnels, Seegmiller developed the Ames Type C Injector that facilitated complete evaporation and uniform particle dispersal. Other researchers, Jeff Brown, Dennis Johnson, John Viegas, and Paul Kutler among them, employed LDV to examine boundary layers near the tunnel walls. One very significant outcome from the LDV studies was the visualization and measurement of a major mechanism of surface drag now known as "sweep and ejection." At least one test program in the HRC1 looked not at airfoils, but at flow separation around tapered changes in a missile's diameter.[203]

Both the HRC1 and HRC2 remain in existence essentially intact, but they have been closed since 1998. They were among the numerous wind tunnels taken out of service during the implementation of NASA's "full cost accounting" program.



High Reynolds Number Channel Number 1. The flow is from right to left, with the nozzle and test section outlined by the bolts on the tunnel's left end. Note the vertical emergency vent and a portion of the High Reynolds Number Channel Number 2 in the background. (Photo credit: NASA AC80-0512-2_1)



This section drawing, with the test section enlarged, shows the High Reynolds Number Channel Number 2's construction. The flexible walls were set to calculated contours before a set of test runs to establish boundary conditions that matched those used in the CFD code. (Image credit: NASA TP-2485, Figs. 3-4)

ENDNOTES

1 NASA has published three books that cover the history of Ames: Edwin P. Hartman, *Adventures in Research: A History of Ames Research Center, 1940–1965* (Washington, DC: NASA, 1970); Elizabeth A. Muenger, *Searching the Horizon: A History of Ames Research Center, 1940–1976* (Washington, DC: NASA, 1985); and Glenn E. Bugos, *Atmosphere of Freedom: Sixty Years at the NASA Ames Research Center* (Washington, DC: NASA SP-4314-2000, 2000).

2 The NACA did not publish a descriptive paper for these tunnels, so dimensional and performance data were taken from "Technical Facilities Capability Catalog," *Technical Memorandum 108691* (Moffett Field, CA: NASA ARC, 1967), pp. 1–10; "Ames Research Facilities Summary (Moffett Field, CA: NASA ARC, 1974), pp. 3–6; and "Research Facilities Handbook," *AHB 8801-1* (Moffett Field, CA: NASA ARC, 1982), pp. 4–7. Copies of these documents are available at the NASA Ames History Office.

3 "N-215, NASA/Army Aerodynamics Lab and 7' by 10' Wind Tunnel #1," State of California Dept. of Parks and Recreation Resource Record, 1995.

4 Thomas A. Harris, "Documentation of the 300-Mile per Hour 7- by 10-Foot Wind Tunnel" (Hampton, VA: NASA LaRC, March 1972), pp. 1–2.

5 Elizabeth A. Muenger, *Searching the Horizon: A History of Ames Research Center, 1940–1976* (Washington, DC: NASA, 1985), pp. 3–6.

6 Ibid., pp. 12–15. Also Walter Vincenti, conversation with author, 18 Aug. 2007.

7 Edwin P. Hartman, *Adventures in Research: A History of the Ames Research Center, 1940–1965* (Washington, DC: NASA, 1970), pp. 45–46.

8 Muenger, *Searching the Horizon,* p. 15.

9 *AHB 8801-1*, pp. 4, 6. Also Glenn E. Bugos, Ames historian, and Arthur E. Ragosta, AFDD Research Support Division chief, to author, 10 July 2009. A good sense of the early and later capabilities and procedures of these tunnels can be gleaned from Victor I. Stevens, William M. Douglass, and Jules B. Dods, Jr., "Wind-Tunnel Investigation of a 1/20-Scale Powered Model of a Four-Engine Transport Airplane," *Wartime Report A-94* (Washington, DC: NACA, 1944) and D. L. Clifton, K. L. Orloff, and G. R. Grant, "Laser Doppler Velocimeter Investigation of Trailing Vortices Behind a Semi-Span Swept Wing in a Landing Configuration," *Technical Memorandum X-62294* (Washington, DC: NASA, 1973). Interestingly, technical reports published by the NACA and NASA rarely identified which of these two tunnels had been used in a particular test program, usually referring to "the Ames 7- by 10-foot tunnel" or "the NASA-Ames 7- by 10-foot wind tunnel" instead, as was done in these reports.

10 Bugos and Ragosta to author, 10 July 2009. Also Ragosta to author, 14 July 2009.

11 Ibid.

12 As with most wind tunnels it opened just before and during World War II, the NACA did not publish a descriptive paper with dimensions for the 16-Foot TT, so most dimensional data were scaled from available photographs and must be considered approximate at best. Though unusual for the mid-1950s, the NACA did not publish a descriptive paper for the rebuilt 14-Foot TT either, nor did technical papers from work done there include significant descriptive material. Various Ames facility catalogs similarly do not include overall drawings of the tunnel or major dimensions. With the tunnel now demolished and records scarce, accurate dimensional data may not now be available.

13 Hartman, *Adventures in Research,* p. 189.

14 *Characteristics of Six Research Wind Tunnels of the Ames Aeronautical Laboratory* (Washington, DC: NACA, 1957), pp. 16–18. This was later cataloged by NASA as *Technical Memorandum 80995*. Also "Research Facilities Handbook," pp. 10–11.

15 James R. Hansen, *Engineer in Charge: A History of the Langley Aeronautical Laboratory, 1917–1958* (Washington, DC: NASA, 1987), pp. 192–194. Also Muenger, *Searching the Horizon*, p. 3.

16 Hartman, *Adventures in Research*, pp. 45–46.

17 Ibid., pp. 32–33. Also Muenger, *Searching the Horizon*, pp. 16–17.

18 Hartman, *Adventures in Research*, p. 36.

19 Ibid., p. 97.

20 Ibid., p. 46.

21 Ibid., pp. 97–99. Also Bugos, *Atmosphere of Freedom*, pp. 17–18. Also James M. Nissen, Burnett L. Gadeberg, and William T. Hamilton, "Correlation of the Drag Characteristics of a P-51B Airplane Obtained from High-Speed Wind-Tunnel and Flight Tests," *Advance Confidential Report 4K02* (Washington, DC: NACA, 1945). Also William T. Hamilton and Warren H. Nelson, "Summary Report on the High-Speed Characteristics of Six Model Wings Having NACA 651-Series Sections," *Technical Report 877* (Washington, DC: NACA, 1945). For a thorough analysis of the problem, see Manley J. Hood and H. Julian Allen, "The Problem of Longitudinal Stability and Control at High Speeds," *Technical Report 767* (Washington, DC: NACA, 1944). For an evaluation of the flaps, see Lee E. Boddy and Walter C. Williams, "A Summary and Analysis of Data on Dive-Recovery Flaps," *Research Memorandum A7F09* (Washington, DC: NACA, 1947).

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23 Hartman, *Adventures in Research*, p. 96.

24 For further discussion of the slot-development problems, see the Langley 16-Foot High-Speed Tunnel section.

25 Hartman, *Adventures in Research*, pp. 188–189.

26 Emmet A. Mossman, "Summary of NACA Submerged-Inlet Investigations," *NACA Conference on Aerodynamic Problems of Transonic Airplane Design* (Moffett Field, CA: NACA Ames Aeronautical Laboratory, 1947), pp. 49–52. Also Charles F. Hall and F. Dorn Barclay, "An Experimental Investigation of NACA Submerged Inlets at High Subsonic Speeds, I–Inlets Forward of the Wing Leading Edge," *Research Memorandum A8B16* (Washington, DC: NACA, 1948).

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28 Jon Bader to James Anderson, "RE: James Meet Jon," 3 February 2023.

29 Most dimensional data for the original tunnel are from C. W. Harper and N. H. Van Dorn, "Discussion of 40- by 80-Foot Wind Tunnel," Naval Historical Center, Aviation History Branch, Washington, DC. This is a description given to a tour group at the facility. It is not dated, but it appears to be early 1950s. Also Alex Roland, *Model Research: The National Advisory Committee for Aeronautics, 1915–1958* (Washington, DC: NASA, 1985), p. 524.

30 William Warmbrodt, "40- by 80- and 80- by 120-Foot Wind Tunnels" (Moffett Field, CA: NASA ARC, 2 July 1997 *https://rotorcraft.arc.nasa.gov/Research/facilities.html*. Also "NFAC 40 × 80 Test Section" (Moffett Field, CA: NASA ARC, n.d.), p. 2.

31 H. Kipling Edenborough, "Research at NASA's NFAC Wind Tunnels," *Technical Memorandum 102827* (Washington, DC: NASA, 1990), p. 1. Also "NFAC 80 × 120 Test Section" (Moffett Field, CA: NASA Ames Research Center, n.d.), p. 10.

32 The modifications needed for dual-circuit operation, including the movable vanes, their operation, and their development, are well described in Gene I. Schmidt, Vernon J. Rossow, Johannes van Aken, and Cynthia L. Parrish, "One-Fiftieth Scale Model Studies of 40- by 80- and 80- by 120-Foot Wind Tunnel Complex at NASA Ames Research Center," *Technical Memorandum 89405* (Washington, DC: NASA, 1987).

33 "National Full-Scale Aerodynamics Complex" (Moffett Field, CA: NASA ARC, n.d.), p. 4, *https://www.arnold.af.mil/About-Us/Fact-Sheets/Display/Article/409302/national-full-scale-aerodynamics-complex/* (accessed 20 March 2024).

34 "NFAC 40 × 80 Test Section," pp. 11–13. Also "NFAC 80 × 120 Test Section," pp. 8–11.

35 Muenger, *Searching the Horizon*, pp. 6–9, 16–17.

36 Ibid., pp. 17, 19.

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41 Schmidt, Rossow, van Aken, and Parrish, "One-Fiftieth Scale Model Studies of 40- by 80- and 80- by 120-Foot Wind Tunnel Complex at NASA Ames Research Center." Also Edenborough, "Research at NASA's NFAC Wind Tunnels," p. 3.

42 William Warmbrodt, Charles A. Smith, and Wayne Johnson, "Rotorcraft Research Testing in the National Full-Scale Aerodynamics Complex at NASA Ames Research Center," *Technical Memorandum 86687* (Washington, DC: NASA, 1985), pp. 1, 4, 9–13. Also Thomas R. Norman, Patrick M. Shinoda, Cahit Kitaplioglu, Stephen A. Jacklin, and Alex Sheikman, "Low-Speed Wind Tunnel Investigation of a Full-Scale UH-60 Rotor System" (Montreal, Canada: American Helicopter Society 58th Annual Forum, 11–13 June 2002).

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51 Roland, *Model Research*, p. 524. Also Graham, *Technical Report 947*, p. 5.

52 Olson and Lawrence, *Research Memorandum A7L24*, pp. 4–5.

53 Earl D. Knechtel, "Experimental Investigation at Transonic Speeds of Pressure Distributions Over Wedge and Circular-Arc Airfoil Sections and Evaluation of Perforated-Wall Interference," *Technical Note D-15* (Washington, DC: NASA, 1959). Also Becker, *The High-Speed Frontier*, p. 53.

54 The tunnel appears in a Feb. 1962 "Ames Research Center Field Installations" document, but not in "Research Facilities Summary: Volume II-Wind Tunnels," Dec. 1965. Copies of these documents are available at the NASA Ames History Office.

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56 Hartman, *Adventures in Research*, pp. 60–62. Also Muenger, *Searching the Horizon*, pp. 37–38.

57 In any supersonic tunnel, there is one particular contour of a converging-diverging nozzle for any given speed and pressure differential. Thus, different speeds require different nozzles, but a flexible wall allows the contour and speed to be adjusted to any value within the tunnel's range.

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59 Ibid., p. 60.

60 Representative reports of test projects during this era include Robert T. Jones, "Characteristics of a Configuration with a Large Angle of Sweepback," *NACA Conference on Aerodynamic Problems of Transonic Airplane Design* (Moffett Field, CA: NACA ARC, 1947), pp. 165–168; Walter G. Vincenti, "Comparison Between Theory and Experiment for Wings at Supersonic Speeds," *Technical Note 2100* (Washington, DC: NACA, 1950); and Dean R. Chapman, William R. Wimbrow, and Robert H. Kester, "Experimental Investigation of Base Pressure on Blunt-Trailing-Edge Wings at Supersonic Velocities," *Technical Note 2611* (Washington, DC: NACA, 1952). Many of these projects used both of the 1- by 3-foot tunnels.

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62 The CMAPS device is described in United States Patent 4189939, 26 Feb. 1980. Harrison West and Bobby R. Delaney, neither of whom was associated with NASA, filed the patent application on 12 Dec. 1977.

63 For a complete description of the PSCL, see M. Harper, "The Propulsion Simulator Calibration Laboratory at Ames Research Center," *Paper 82-0574* (Reston, VA: AIAA, 1982). The current condition was noted by the author during an inspection of the PSCL on 6 Nov. 2007.

64 Hartman, *Adventures in Research*, pp. 61–62. Also Dean R. Chapman, William R. Wimbrow, and Robert H. Kester, "Experimental Investigation of Base Pressure on Blunt-Trailing-Edge Wings at Supersonic Velocities," *Technical Note 2611* (Washington, DC: NACA, 1952), p. 4. Also "1- by 3-Foot Supersonic Wind Tunnel Section," *NACA Ames Aeronautical Laboratory, Moffett Field, California*, AFS1070.8A, History Office, NASA Ames Research Center, n.d. (information within indicates a probable date of 1946).

65 Hartman, *Adventures in Research*, pp. 60–62. Also Muenger, *Searching the Horizon*, pp. 37–38.

66 Test reports for these projects include Robert T. Jones, "Characteristics of a Configuration with a Large Angle of Sweepback," *NACA Conference on Aerodynamic Problems of Transonic Airplane Design* (Moffett Field, CA: NACA Ames Aeronautical Laboratory, 1947), pp. 165–168; and Chapman, Wimbrow, and Kester, *Technical Note 2611*. Many of these projects used both of the 1- by 3-foot tunnels.

67 Bader to Anderson, "RE: James Meet Jon."

68 Michael Ospring comment from Maureen Delgado to James Anderson, "RE: FOR REVIEW: Wind Tunnels of NASA," 30 January 2023.

69 No single document fully describes this tunnel. Except as otherwise noted, design and performance data were assembled from several sources, including "Research Facilities Summary: Volume II-Wind Tunnels" (Moffett Field, CA: NASA Ames Research Center, 1965), pp. 6.1–6.8; "Characteristics of Six Research Wind Tunnels of the Ames Aeronautical Laboratory," *Technical Memorandum 80995* (Washington, DC: NACA, 1957), pp. 25–36; and "Research Facilities Handbook," *AHB 8801-1* (Moffett Field, CA: NASA ARC, 1982), pp. 8–9.

70 Frank Kmak comment from Maureen Delgado to James Anderson, "RE: FOR REVIEW: Wind Tunnels of NASA," 30 January 2023.

71 Robert M. Reynolds, Donald A. Buell, and John H. Walker, "Investigation of an NACA 4-(5)(05)-041 Four-Blade Propeller with Several Spinners at Mach Numbers up to 0.90," *Research Memorandum A52I19a* (Washington, DC: NACA, 1952), pp. 15–17.

72 Michael Ospring and Frank Kmak comments from Maureen Delgado to James Anderson, "RE: FOR REVIEW: Wind Tunnels of NASA," 30 January 2023.

73 For post-reconstruction data, see Mike Mewhinney, "Unique NASA Wind Tunnel Restoration Complete," *Release 94-193* (Moffett Field, CA: NASA ARC, 16 Nov. 1994) and Mike Mewhinney, "Refurbished Wind Tunnel to Open at NASA Ames Research Center," *Release 95-143* (Moffett Field, CA: NASA ARC, 21 Aug. 1995).

74 For post-reconstruction data, see Mewhinney, "Unique NASA Wind Tunnel Restoration Complete," and Mewhinney, "Refurbished Wind Tunnel to Open at NASA Ames Research Center."

75 Bader to Anderson, "RE: James Meet Jon."

76 Hartman, *Adventures in Research*, pp. 54–55.

77 A hydrostatic test employs essentially incompressible water under pressure to verify the integrity of a pressure vessel. Since the mass and volume of water change very little under pressure, only a small volume must escape if a rupture occurs. This eliminates the possibility for an explosion that could occur if a compressed gas was used. Hydrostatic tests typically pressurize the vessel to 1.5 times its design pressure.

78 Ibid., p. 58. Also Baals and Corliss, *Wind Tunnels of NASA*, pp. 32–33.

79 Hartman, *Adventures in Research*, p. 58.

80 Reports of representative projects include Ben H. Johnson, Jr., "Investigation of a Thin Wing of Aspect Ratio 4 in the Ames 12-Foot Pressure Wind Tunnel, I–Characteristics of a Plain Wing," *Research Memorandum A8D07* (Washington, DC: NACA, 1948) (Parts II and III of this investigation examined the wing with various flap configurations); Reynolds, Buell, and Walker, *Research Memorandum A52I19a*; and Scott O. Kjelgaard and Harry L. Morgan, Jr., "Pressure Distribution Data from Tests of 2.29 M (7.5 ft) Span EET High-Lift Transport Aircraft Model in the Ames 12-Foot Pressure Tunnel," *Technical Memorandum 84517* (Washington: NASA, 1983).

81 Michael Ospring comment from Maureen Delgado to James Anderson, "RE: FOR REVIEW: Wind Tunnels of NASA," 30 January 2023.

82 Ibid.

83 Bader to Anderson, "RE: James Meet Jon."

84 George H. Kidwell, Director (Acting), Research and Development Services, to Ames staff, "Update on the Wind Tunnel Closures," 5 June 2003, copy available at *https://spaceref.com/status-report/nasa-ames-research-center-update-on-the-wind-tunnel-closures/* (accessed 20 March 2024).

85 Bader to Anderson, "RE: James Meet Jon."

86 Descriptive and performance data for this tunnel were compiled from *Characteristics of Six Research Wind Tunnels of the Ames Aeronautical Laboratory* (Washington, DC: NACA, 1957), pp. 37–46; and *Research Facilities Summary, Vol. II—Wind Tunnels* (Moffett Field, CA: NASA Ames Research Center, 1965), pp. 2.1–2.7.

87 "National Register of Historic Places Registration Form for Ames Aeronautical Laboratory 6 × 6 Foot Supersonic Wind Tunnel," *OMB No. 1024-0018*, submitted to Wayne Donaldson, State Historic Preservation Officer, Sacramento, CA, by Keith H. Venter, Ames Facility Historic Preservation Officer, 7 Nov. 2006, section 7, pp. 1–4.

88 *Characteristics of Six Research Wind Tunnels*, pp. 39, 46.

89 This story is recounted in Hartman, *Adventures in Research*, pp. 63–64; Muenger, *Searching the Horizon*, p. 39; and Bugos, *Atmosphere of Freedom: Sixty Years at the NASA Ames Research Center*, p. 33.

90 Hartman, Adventures in Research, 65–66. Also H. Julian Allen, "The Asymmetric Adjustable Supersonic Nozzle for Wind Tunnel Application," Research Memorandum A8E17 (Washington, DC: NACA, 1948).

91 Bugos, *Atmosphere of Freedom*, p. 33. Also Roland, *Model Research*, p. 526.

92 Bugos, *Atmosphere of Freedom*, p. 33. Typical reports for research projects include Charles F. Hall, "Lift, Drag, and Pitching Moment of Low-Aspect-Ratio Wings at Subsonic and Supersonic Speeds," *Research Memorandum A53A30* (Washington, DC: NACA, 1953); Frank A. Lazzeroni, "Investigation of a Missile Airframe with Control Surfaces Consisting of Projecting Quadrants of the Nose Cone," *Research Memorandum A53L21* (Washington, DC: NACA, 1954); and Earl R. Keener and Jack J. Brownson, "Wind-Tunnel Investigation of the Aerodynamic Characteristics of the M2-F2 Lifting-Body Entry Configuration at Transonic and Supersonic Mach Numbers," *Technical Memorandum X-2511* (Washington, DC: NASA, 1972). John W. Boyd, who held several positions at Ames, recalled several of the aircraft programs in a 3 Oct. 2005 interview with Jennifer Ross-Nazzal, available at the NASA Headquarters History Office, Washington, DC, pp. 13–15. Also "National Register of Historic Places Registration Form," section 8, pp. 2–3.

93 F. K. Owen, G. M. Orngard, and T. K. McDevitt, "A New 3D LDV System for the NASA Ames 6 × 6 ft. Wind Tunnel," *Eleventh International Congress on Instrumentation in Aerospace Simulation Facilities*, Stanford, CA, 26–28 Aug. 1985 (New York: Institute of Electrical and Electronics Engineers, 1985), pp. 257–262.

94 "National Register of Historic Places Registration Form," section 7, p. 2. Also John W. Boyd interview, p. 36.

95 Descriptive information was compiled from Alvin Seiff, Carlton S. James, Thomas N. Canning, and Alfred G. Boissevain, "The Ames Supersonic Free-Flight Wind Tunnel," *RM A52A24* (Washington, DC: NACA, 1952); *Research Facilities Summary, Vol. I—Guns and Ranges* (Moffett Field, CA: NASA ARC, 1965), pp. 5.1–5.6; and Robert J. Carros and Charles E. DeRose, "Counterflow Facilities," *Ballistic Range Technology* (Neuilly sur Seine, France: Advisory Group for Aerospace Research and Development [AGARD], 1970), pp. 170–172.

96 Carros and DeRose, "Counterflow Facilities," p. 170.

97 Seiff, James, Canning, and Boissevain, *RM A52A24*, p. 7.

98 Ibid., pp. 6–7.

99 Ibid., pp. 9–17. Also Alfred G. Boissevain and Peter F. Intrieri, "Determination of Stability Derivatives from Ballistic Range Tests of Rolling Aircraft Models," *Technical Memorandum X-399* (Washington, DC: NASA, 1961).

100 Carros and DeRose, "Counterflow Facilities," pp. 170–171.

101 *Research Facilities Summary, Vol. I—Guns and Ranges*, pp. 5.1–5.6; and "Technical Facilities Capability Catalog," *Technical Memorandum 108691* (Moffett Field, CA: NASA ARC, 1967).

102 For hypersonic tunnels, "conventional" refers to blowdown-type tunnels with test times measured in seconds or minutes, as opposed to "shock" or "impulse" hypersonic tunnels that produce very high Mach numbers, but only for milliseconds.

103 Descriptive data for the tunnel are from A. J. Eggers, Jr., and George J. Nothwang, "The Ames 10- by 14-Inch Supersonic Wind Tunnel," *Technical Note 3095* (Washington, DC: NACA, 1954).

104 The x-ray densitometer system for the 10 ′ 14 HYST is described in John Dimeff, Ralph K. Halett, Jr., and C. Frederick Hansen, "X-Ray Instrumentation for Density Measurements in a Supersonic Flow Field," *Technical Note 2845* (Washington, DC: NACA, 1952).

105 Ibid., p. 2.

106 Ibid., p. 3. Also Baals and Corliss, *Wind Tunnels of NASA*, p. 57. Also Hartman, *Adventures in Research*, p. 300.

107 Eggers and Nothwang, *Technical Note 3095*, p. 57. Also Hartman, *Adventures in Research*, p. 185.

108 Stanford E. Neice, "Experimental Investigation of the Aerodynamic Characteristics of a Ballistic-Type Missile," *Research Memorandum A54C04* (Washington, DC: NACA, 1954).

109 Hartman, *Adventures in Research*, p. 413.

110 Descriptive information for the original tunnel is from Joseph M. Spiegel and Leslie F. Lawrence, "A Description of the Ames 2- by 2-Foot Transonic Wind Tunnel and Preliminary Evaluation of Wall Interference," *Research Memorandum A55I21* (Washington, DC: NACA, 1956), pp. 4–7.

111 Edward T. Schairer, George Lee, and T. Kevin McDevitt, "A Two-Dimensional Adaptive-Wall Test Section with Ventilated Walls in the Ames 2- by 2-Foot Transonic Wind Tunnel," *Technical Memorandum 102207* (Washington, DC: NASA, 1989), pp. 4–10.

112 Hartman, *Adventures in Research*, pp. 188–189. Also Spiegel and Lawrence, *Research Memorandum A55I21*, p. 18.

113 One typical project was reported in Leland H. Jorgensen, "Elliptic Cones Alone and with Wings at Supersonic Speeds," *Technical Report 1376* (Washington, DC: NACA, 1957). For the color-schlieren technique, see Spiegel and Lawrence, *Research Memorandum A55I21*, p. 19.

114 R. B. Kingsland, ed., "Experimental Results of Tests to Determine the Effects of Orbiter Thermal Protection System (TPS) Tiles on Panel Flutter Conducted in the Ames Research Center 2 × 2-Foot Transonic Wind Tunnel," NASA *Contractor Report 151,775* (New Orleans, LA: Chrysler Corporation Michoud Defense-Space Div., 1979). Also J. G. R. Collette, "Phase II Screening Tests of AFRSI Material Using Model 115-0 in the Ames Research Center 2 × 2-Foot Transonic Wind Tunnel," NASA *Contractor Report 160,848* (New Orleans, LA: Chrysler Huntsville Electronics Div., 1981).

115 Edward T. Schairer and Joel P. Mendoza, "Adaptive-Wall Wind-Tunnel Research at NASA-Ames Research Center," *Technical Memorandum 84236* (Washington, DC: NASA, 1982); Edward T. Schairer," Methods for Assessing Wall Interference in the 2- by 2-Foot Adaptive-Wall Wind Tunnel," *Technical Memorandum 88252* (Washington, DC: NASA, 1986); and Edward T. Schairer, George Lee, and T. K. Modevitt, "Two-Dimensional Adaptive-Wall Tests in the NASA Ames 2- by 2-Foot Transonic Wind Tunnel," *Journal of Aircraft 28* (Nov. 1991): 673–682.

116 Maureen Delgado to James Anderson, "RE: FOR REVIEW: Wind Tunnels of NASA," 30 January 2023.

117 Descriptive data are from "Manual for Users of the Unitary Plan Wind Tunnel Facilities of the National Advisory Committee for Aeronautics," *Technical Memorandum 80998* (Washington, DC: NACA, 1956), pp. 43–64; and *Unitary Plan Wind Tunnel: An ASME International Historic Mechanical Engineering Landmark* (New York: American Society of Mechanical Engineers, 1996). Also Bader to Anderson, "RE: James Meet Jon."

118 Bader to Anderson, "RE: James Meet Jon."

119 *Unitary Plan Wind Tunnel*, pp. 2, 6.

120 Bader to Anderson, "RE: James Meet Jon."

121 These are nominal values. Various sources list Mach numbers as low as 0.3 and as high as 1.5 for this tunnel.

122 Bader to Anderson, "RE: James Meet Jon," p. 6. Also *Technical Memorandum 80998*, pp. 45–46, 56–57.

123 See the Langley Unitary Plan Wind Tunnel section for further description and illustrations of similar sliding-block nozzles.

124 Frank Kmak comment from Maureen Delgado to James Anderson, "RE: FOR REVIEW: Wind Tunnels of NASA," 30 January 2023.

125 *Technical Memorandum 80998*, pp. 46, 58–59; Bader to Anderson, "RE: James Meet Jon."

126 *Technical Memorandum 80998*, pp. 46, 59–61.

127 *Technical Memorandum 80998*, pp. 49–50, 64.

128 "National Program of Transsonic [*sic*] and Supersonic Wind Tunnels," Report of the Special Committee on Supersonic Facilities to the National Advisory Committee on Aeronautics, 24 Jan. 1947, NASA Langley Archives, Milton Ames Collection, box 5.

129 For further discussion of the Unitary Plan's development, see R. D. Launius, T. D. Irvine, and E. A. Arrington, "NACA/NASA and the National Unitary Wind Tunnel Plan, 1945–1965," *Paper A02-14248* (Reston, VA: AIAA, 2002), pp. 1–6. Also Roland, *Model Research*, pp. 211–221.

130 *Unitary Plan Wind Tunnel*, p. 2. For a technical treatise on the design process for large, high-speed wind tunnels, including the UPWT, see Ralph F. Huntsberger and John F. Parsons, "The Design of Large High-Speed Wind Tunnels," Advisory Group for Aerospace Research and Development (AGARD) Fourth General Assembly, Wind-Tunnel Panel, Scheveningen, Netherlands, 4 May 1954.

131 Although most of the commercial airliner tests generated proprietary reports for the manufacturer, photographs of airliners in the transonic test section exist for most American jetliners. For Space Shuttle testing, three of the many test reports are R. B. Hardin and R. R. Burrows, "Wind Tunnel Tests of an 0.019-Scale Space Shuttle Integrated Vehicle -2A Configuration (Model 14-OTS) in the NASA Ames 8 × 7-Foot Wind Tunnel," *Contractor Report 141519* (Washington, DC: NASA, 1975); E. Chee, "Results of a Pressure Loads Investigation on a 0.030-Scale Model (47-OTS) of the Integrated Space Shuttle Vehicle Configuration 5 in the NASA Ames Research Center 9 × 7 Foot Leg of the Unitary Plan Wind Tunnel," 5 vols., *Contractor Report 141819* (Washington, DC: NASA, 1975); and P. J. Hawthorne, "Terminal Area Energy Management Regime Investigations Utilizing an 0.030-Scale Model (47-O) of the Space Shuttle Vehicle Orbiter Configuration 140A/B/C/R in the Ames Research Center 11 × 11 Foot Transonic Wind Tunnel," 13 vols., *Contractor Report 147603* (Washington, DC: NASA, 1976). One of the more interesting reports about a NASA research project is Ronald C. Smith, Robert T. Jones, and James L. Summers, "Transonic Lateral and Longitudinal Control Characteristics of an F-8 Airplane Model Equipped with an Oblique Wing," *Technical Memorandum X-73103* (Washington, DC: NASA, 1976).

132 Frank J. Kmak," Modernization and Activation of the NASA Ames 11- by 11-Foot Transonic Wind Tunnel," *Paper 2000-2680* (Reston, VA: AIAA, 2000), pp. 1–2, 6.

133 Frank Kmak comment from Maureen Delgado to James Anderson, "RE: FOR REVIEW: Wind Tunnels of NASA," 30 January 2023.

134 For details of the extensive work accomplished, see ibid., pp. 3–8. Also Sreedhara V. Murthy, Frank J. Kmak, and Brian R. Koss, "The Design and Installation of a Turbulence Reduction System for the NASA Ames 11- by 11-Foot Transonic Wind Tunnel," *Paper 98-2705* (Reston, VA: AIAA, 1998).

135 "Unitary Plan Wind Tunnel," National Historic Landmarks Program, National Park Service, *https://www.nps.gov/places/unitary-plan-wind-tunnel.htm* (accessed 30 October 2023).

136 Descriptive and operational information for the AES is from Carlton Bioletti, "An Atmospheric Entry Simulator," *Technical Memorandum X-51119* (Washington, DC: NASA, 1959).

137 A. J. Eggers, Jr., "A Method for Simulating the Atmospheric Entry of Long-Range Ballistic Missiles," *Research Memorandum A55I15* (Washington, DC: NACA, 1956).

138 Bioletti, *Technical Memorandum X-51119*, p. 5. Also Baals and Corliss, *Wind Tunnels of NASA*, pp. 75–76.

139 Bioletti, *Technical Memorandum X-51119*, pp. 8–11.

140 Hartman, *Adventures in Research*, pp. 336–338.

141 Descriptive information was compiled from *Research Facilities Summary, Vol. I—Guns and Ranges* (Moffett Field, CA: NASA ARC, 1965), pp. 6.1–6.8; "Ames Research Facilities Summary" (Moffett Field, CA: NASA ARC, 1974), pp. 43–44; and "Research Facilities Handbook," *AHB 8801-1* (Moffett Field, CA: NASA ARC, 1982), pp. 56–57. Interestingly, a research report by the Eloret Institute (cited in note 5) indicates that pressures of up to 6 atmospheres were used in 1987, casting doubt on any pressure restriction during its service life, or at least any below 6 atmospheres.

142 Charles Cornelison comments from David Hash to James Anderson, "FOR REVIEW: Wind Tunnels of NASA," 14 January 2023.

143 Ibid.

144 *Research Facilities Summary, Vol. I*, p. 6.2.

145 For a thorough explanation of the light-gas gun, see A. C. Charters, B. Pat Denardo, and Vernon J. Rossow, "Development of a Piston-Compressor Type Light-Gas Gun for the Launching of Free-Flight Models at High Velocity," *Technical Note 4143* (Washington, DC: NACA, 1957).

146 *Research Facilities Summary, Vol. I*, p. 6.2. Also P. F. Intrieri and D. B. Kirk, "High-Speed Aerodynamics of Several Blunt-Cone Configurations," *Paper 86-0300* (Reston, VA: AIAA, 1986), p. 2.

147 Reports of test programs conducted in the PBR include Thomas N. Canning, Michael E. Tauber, and Max E. Wilkins, "Review of Recent Ballistic Range Boundary-Layer Transition Work on Ablating Bodies at Ames," *Technical Memorandum X-60314* (Washington, DC: NASA, 1967); Paul F. Intrieri and Donn B. Kirk, "Ballistic Range Measurements of the Drag and Static and Dynamic Stability of a Recoverable Space Shuttle Booster Vehicle," *Technical Memorandum X-62124* (Washington, DC: NASA, 1972); Intrieri and Kirk, *Paper 86-0300*; and Gary Chapman and Jim Arnold, Eloret Institute, "Experimental Investigation of Hypersonic Aerodynamics: Semi-Annual Research Report for the Period April 1, 1987–September 30, 1987," *Contractor Report 181374* (Washington, DC: NASA, 1987).

148 Charles Cornelison comments from David Hash to James Anderson, "FOR REVIEW: Wind Tunnels of NASA," 14 January 2023.

149 Brian Cantwell and George S. Diewert, "Development of a Detonation Driver for the NASA-Ames Hypersonic Shock Tube Facility," *Contractor Report 202438* (Washington, DC: NASA, 1996).

150 NASA has been using the Army's Aberdeen range for aeroballistic testing to some extent. Michael Wilder, sent as attachment to James Anderson, "FOR REVIEW: Wind Tunnels of NASA," 18 January 2023.

151 The Hypervelocity Free-Flight Facility section was heavily edited by Ames Senior Facilities Technologies Charles Cornelison. Information sent as attachment in David Hash to James Anderson, "FOR REVIEW: Wind Tunnels of NASA," 15 January 2023.

152 M. C. Wilder, D. W. Bogdanoff, and C. J. Cornelison, "Hypersonic Testing Capabilities at the NASA Ames Ballistic Ranges," *AIAA Paper 2015-3339*, January 2015.

153 J. Brown, D. Bogdanoff, L. Yates, M. Wilder, and S. Murman, "Complex-Trajectory Aerodynamics Data for Code Validation from a New Free-Flight Facility," *AIAA-2006-662*, 44th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, 9–12 January 2006.

154 Descriptive and performance data were compiled from *Research Facilities Summary, Vol. I–Guns and Ranges* (Moffett Field, CA: NASA Ames Research Center, 1965), pp. 1.1–1.9; and "Research Facilities Handbook," *AHB 8801-1* (Moffett Field, CA: NASA ARC, 1982), pp. 58–59. Also Charles Cornelison comment, 15 January 2023.

155 Cornelison comment, 15 January 2023.

156 Ibid.

157 Hartman, *Adventures in Research*, pp. 331–332.

158 *Research Facilities Summary*, pp. 3.1–3.4. Also Hartman, *Adventures in Research*, p. 331. Also William A. Page, Thomas N. Canning, Roger A. Craig, and Jack D. Stephenson, "Measurements of Thermal Radiation of Air from the Stagnation Region of Blunt Bodies Traveling at Velocities up to 31,000 Feet per Second," *Technical Memorandum X-508* (Washington, DC: NASA, 1961), pp. 3–4.

159 *Research Facilities Summary*, pp. 2.1–2.6. Also Hartman, *Adventures in Research*, p. 332. Also Alvin Seiff, "A Progress Report on the Ames Hypervelocity Free-Flight Facilities and Some of the Current Research Problems Being Studied in Them," *Technical Memorandum X-57444* (Washington, DC: NASA, 1963), pp. 4–9.

160 Typical reports of tests include Layton Yee, "Free-Flight Measurements of Heat Transferred to the Apollo Afterbody with and without Heat Shield Ablation," *Technical Memorandum X-1096* (Washington, DC: NASA, 1965); and Seiff, "A Progress Report on the Ames Hypervelocity Free-Flight Facilities and Some of the Current Research Problems Being Studied in Them," pp. 12–20.

161 Discontinuance of this film's production in the 1970s required a change to a different, panchromatic film that the safelights partially exposed. New, "light-tight" film canisters solved the problem. In 2014, the film cameras were replaced with digital cameras.

162 Charles J. Cornelison, "Status Report for the Hypervelocity Free-Flight Aerodynamic Facility," 48th Aeroballistic Range Association Meeting, Austin, TX, Nov. 1999, pp. 2–6.

163 Hartman, *Adventures in Research*, p. 419. Also Seiff, "A Progress Report on the Ames Hypervelocity Free-Flight Facilities and Some of the Current Research Problems Being Studied in Them," pp. 9–12.

164 Ernest F. Fretter, "NASA Ames Arc Jets and Range, Capabilities for Planetary Entry," 2nd International Planetary Probe Workshop, NASA Ames Research Center, April 2005, p. 316.

165 Cornelison, "Status Report for the Hypervelocity Free-Flight Aerodynamic Facility," p. 2.

166 Ibid., pp. 1–2.

167 Cornelison comment, 15 January 2023.

168 Description and performance data for the original facility are from Bernard E. Cunningham and Samuel Kraus, "A 1-Foot Hypervelocity Shock Tunnel in Which High-Enthalpy, Real-Gas Air Flows Can Be Generated with Flow Times of About 180 Milliseconds," *Technical Note D-1428* (Washington, DC: NASA, 1962), pp. 3–7, 12–14.

169 David A. Stewart and Robert E. Dannenberg, "A Note on Wire Ignition in Combustion-Heated Drivers for Shock-Tunnel Applications," *Technical Note D-3063* (Washington, DC: NASA, 1962), p. 3.

170 Cunningham and Krauss, *Technical Note D-1428*, pp. 7–11. Also William J. Loubsky, Robert S. Hiers, and David A. Stewart, "Performance of a Combustion Driven Shock Tunnel," *Technical Memorandum X-54960* (Washington, DC: NASA, 1964), p. 4.

171 There is no set threshold for the hypervelocity regime, but it is generally considered to be the speed above which the shock produces temperatures and pressures high enough to cause chemical changes, known as "real gas" effects, in the air that alter its aerodynamic and thermodynamic properties. These real gas effects typically become significant at about Mach 10.

172 Baals and Corliss, *Wind Tunnels of NASA*, pp. 81–82, 86.

173 Ames developed an additional technique, the arc-jet tunnel, during the 1960s. Since arc-jets were primarily used for high-temperature materials testing rather than aerodynamics, they are not included in this book.

174 Facilities employing all of these concepts are discussed in other sections of this book. Also see Hartman, *Adventures in Research*, pp. 330–331.

175 Cunningham and Krauss, *Technical Note D-1428*, p. 3. Also Hartman, *Adventures in Research*, p. 331. Also Loubsky, Hiers, and Stewart, *Technical Memorandum X-54960*, p. 13.

176 Reports on these test programs include Loubsky, Hiers, and Stewart, *Technical Memorandum X-54960*; Joseph G. Marvin and Clifford M. Akin, "Pressure and Convective Heat-Transfer Measurements in a Shock Tunnel Using Several Test Gases," *Technical Note D-3017* (Washington, DC: NASA, 1965); and Robert S. Hiers, Jr., and John O. Reller, Jr., "Analysis of Nonequilibrium Air Streams in the Ames 1-Foot Shock Tunnel," *Technical Note D-4985* (Washington, DC: NASA, 1965).

177 Thorval Tendeland and B. Douglas Pearson, Jr., "Effectiveness of Two Flap Controls on a Mercury Type Capsule at a Mach Number of 15 in the Ames Hypersonic Helium Tunnel," *Technical Memorandum X-660* (Washington, DC: NASA, 1962), pp. 3–4.

178 Ibid., p. 3. Also Hartman, *Adventures in Research*, pp. 284–285.

179 Tendeland and Pearson, *Technical Memorandum X-660*, p. 3.

180 Ibid., p. 4.

181 Hartman, *Adventures in Research*, pp. 284–285, 331–332.

182 See the Langley Hypersonic Facilities Complex section for more on these tunnels.

183 For a thorough treatise on the problems, see Eugene S. Love, Arthur Henderson, Jr., and Mitchel H. Bertram, "Some Aspects of Air-Helium Simulation and Hypersonic Approximations," *Technical Note D-49* (Washington, DC: NASA, 1959).

184 Hartman, *Adventures in Research*, pp. 285, 329–330.

185 Ibid., p. 330.

186 Tendeland and Pearson, *Technical Memorandum X-660* describes one of these test programs. For other test programs, see Joseph H. Kemp, Jr., "Telemetry Measurements of Afterbody Pressures on Free-Flying Models of the Apollo Capsule at Mach Numbers from 10 to 21 in Helium and 14 in Air," *Technical Memorandum X-1154* (Washington, DC: NASA, 1965); Joseph G. Marvin, "Pressure and Heat-Transfer Distribution on the Afterbody of a Lifting Mercury-Type Capsule at Mach Number 15 in Helium," *Technical Memorandum X-783* (Washington, DC: NASA, 1963); and David A. Stewart and Mamoru Inouye, "Shock Shapes and Pressure Distributions for Large Angle Pointed Cones in Helium at Mach Numbers of 8 and 20," *Technical Note D-5343* (Washington, DC: NASA, 1969).

187 Descriptive and performance data were compiled from John O. Reller, Jr., "Design and Performance of the Ames Electric-Arc Shock Tunnel," *Technical Memorandum X-2814* (Washington, DC: NASA, 1973); and "Research Facilities Handbook," *AHB 8801-1* (Moffett Field, CA: NASA ARC, 1982), pp. 38–39.

188 The terminology is curious because shock facilities that incorporate a secondary diaphragm, nozzle, and test section outlet at the end of their driven tubes are generally referred to as shock *tunnels*, while those with solid driven tube ends are commonly called shock *tubes*. According to Ames research scientist Brett Cruden, EAST was originally built as a tunnel, but it has long been used as a "tube" only. It was probably used in both modes from the very beginning.

189 For a complete description of the data acquisition system developed for the EAST, see L. Mazer and H. L. Seegmiller, "A 500,000 Sample per Second Digital Recorder for the Ames Electric Arc Shock Tunnel," *3rd International Congress on Instrumentation in Aerospace Simulation Facilities* (Farmingdale, NY: Polytechnic Institute of Brooklyn, 5–8 May 1969), pp. 243–247.

190 Reller, *Technical Memorandum X-2814*, pp. 1–2. Historical documents for the EAST are few, with this paper having the best-known discussion of its design and early development. Other important historical documents for EAST include R. E. Dannenberg and A. F. Silva, "Arc Driver Operation for Either Efficient Energy Transfer or High-Current Generation," *TM X-62162* (NASA, May 1972); and R. E. Dannenberg and A. F. Silva, "Exploding Wire Initiation and Electrical Operation of a 40-kV System for Arc-heated Drivers up to 10 Feet Long," *TN D-5126* (NASA, April 1969).

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As this 2006 aerial view shows, the John H. Glenn Research Center at Lewis Field is confined between Cleveland's Hopkins International Airport and the heavily wooded ravine of the Rocky River. (Photo credit: NASA GRC-2006-C-01660)

JOHN H. GLENN RESEARCH CENTER AT LEWIS FIELD

John H. Glenn, Jr.
(Photo credit: NASA GPN-2000-001175)

In 1939, as the NACA began to build its second laboratory at Moffett Field, California, it also began to consider the merits of a third laboratory that could focus on aircraft propulsion. The Langley Laboratory in Hampton, Virginia, had constructed some facilities for engine and propeller research and made significant contributions in the field, including the famous NACA cowl for radial engines and improved airfoils for propellers, but Langley's main focus was aerodynamics, not engine performance. That had been left to the engine manufacturers. The 1930s had, however, vastly expanded the operating environment for engines, just as it had for airframes, and it became clear to the NACA that a laboratory dedicated to propulsion research would undoubtedly pay large dividends.

Just as the NACA's Director of Aeronautical Research, George W. Lewis, and a special committee had strongly recommended a second aeronautical laboratory on the West Coast, Charles Lindbergh led another committee that evaluated the status of European aviation, and it recommended that the NACA build a third laboratory—one specifically for engine research. Unlike the aircraft builders, the engine manufacturers were skeptical about government involvement in what had been their exclusive territory, especially after a wind tunnel was proposed for the new laboratory. George Mead, a renowned authority on aircraft engines and chairman of the NACA's Power Plants Committee, understood the difference between "fundamental research" and "development," as well as the competitive nature of the business, having worked as an engineer and executive

for both Wright Aeronautical and Pratt & Whitney, America's two largest aircraft engine manufacturers. He understood the need and value of an engine-testing facility that could produce the high-altitude conditions that engines would increasingly experience, and he knew that the manufacturers were not likely to invest in such a facility anytime soon. To bolster his case, Mead consulted other experts like propeller engineer Frank W. Caldwell, who also supported what became the Altitude Wind Tunnel (AWT). The Power Plant Committee's recommendation to build it remained controversial, but Executive Committee Chairman Vannevar Bush, Lindbergh, and Lewis argued the case passionately before Congress, which agreed to fund the Aircraft Engine Research Laboratory (AERL), including the AWT and the Engine Research Building, in 1940. With funding secured, the NACA appointed Mead to lead the team that designed the initial portions of the AERL.

George W. Lewis. (Photo credit: NASA GRC-1998-C-00215)

Selecting the site proved to be a challenge. Lewis wanted the new AERL to be located close to the engine and parts manufacturers. The NACA evaluated 62 sites in the Midwest. Cleveland, Ohio, won the competition by agreeing, among other things, to provide 200 acres of land adjacent to its municipal airport (the NACA would later buy an additional 150 acres). Groundbreaking on 23 January 1941 required not only a shovel, but also a pick to break the frozen earth.[1]

The AERL's early facilities included the Engine Research Building that housed a wide variety of laboratories to study virtually every aspect of piston engines design, including combustion, lubrication, cooling, materials, and fuel, and the AWT, Mead's large wind tunnel able to run complete engines and propellers at simulated altitudes of up to 55,000 feet. In addition to massive exhaust blowers to lower the operating pressure, the AWT included a 7,000-ton refrigeration plant to cool the test air to –47°F. These and a few other early facilities were in service by mid-1944, and they made significant contributions during the last year of the war effort, notably improvements in cooling the Wright R-3350 engines used in Boeing B-29 Superfortress bombers.

Although the AERL, renamed the Lewis Flight Propulsion Laboratory (LFPL) in 1948, had originally been designed to do piston engine research, its first wind tunnel test was of a Bell P-59 Airacomet, America's first jet fighter. This test, done in secret,

foretold the laboratory's future, and the bulk of work done at the LFPL following World War II involved turbojet, ramjet, and, later, rocket engines. During the early Cold War era of the late 1940s and 1950s, Congress made large allocations to all of the NACA laboratories, including the Unitary Plan to build large supersonic tunnels at each laboratory plus a new Air Force research and development center. The LFPL's Unitary Plan Wind Tunnel entered service in 1955, powered by seven electric motors totaling 250,000 horsepower, making it the world's most powerful wind tunnel. (A 1990 rewinding raised this to over 290,000 horsepower.) In this, and other LFPL tunnels, such as the 8- by 6-Foot Supersonic Wind Tunnel, engines could, and still can, be operated at conditions simulating flight conditions. The LFPL even began investigating the possibilities of using nuclear energy to propel airplanes and spacecraft during the 1950s, and the laboratory established a satellite facility, Plum Brook Station (today, the Armstrong Test Facility), for nuclear engine research near Sandusky, Ohio, in 1956.

In addition to propulsion research, the Lewis Laboratory used the AWT's massive refrigeration plant to support work in an unrelated, but equally crucial, research area: ice buildup on airplanes. Testing in the Icing Research Tunnel and flight testing over Lake Erie discovered much of what is known about icing and its prevention, thus saving untold lives.

With the creation of NASA in 1958, the laboratory became the Lewis Research Center (LeRC), but the center's mission did not radically change. LeRC's work with liquid-hydrogen rocket engines expanded with the RL-10 program that same year. Turbojet and turbofan testing, dormant for several years, resumed in 1966 and continues today. Later research work has involved topics such as advanced propellers and noise reduction, with significant improvements developed at LeRC now standard practice in the industry.

In 1999, NASA renamed the Cleveland center once again—this time to honor astronaut and Senator John H. Glenn, Jr., an Ohio native—but the agency did not want to forget its heritage in the process. Accordingly, the center became the John H. Glenn Research Center at Lewis Field. Like other NASA centers, Glenn has responded to the leaner budgets and changing research needs of the 21st century by refocusing its efforts to support new space endeavors like the Constellation Program while maintaining its place as NASA's premier facility for testing powerplants.

Armstrong Test Facility (formerly Plum Brook Station)

Glenn's satellite facility, the Armstrong Test Facility, came into being in 1941 as the Plum Brook Ordnance Works, an Army munitions plant named for a creek that ran through the 9,000-acre site near Sandusky, Ohio. The plant produced a variety of explosive weapons throughout World War II; but having no need for the facility after the war, the Army removed the weapons stored in earth-covered concrete bunkers and closed the works. It remained idle until 1956, when the NACA began looking for a remote site that would be suitable for a nuclear reactor to support research on the effects of radiation on nuclear-powered aircraft.

Plum Brook seemed suitable, and the NACA acquired 500 acres of the site for its reactor facility, which became operational in 1962, following a long design and construction period. The 60-megawatt Plum Brook Reactor Facility, NASA's only nuclear test reactor, operated from 1962 through 1973, when it was shut down and put into "safe dry storage" mode after its fuel was removed and sent to a Department of Energy facility. Its initial duty was the irradiation of materials for later examination in an adjacent "hot lab," but its mission shifted in 1961, when NASA and the Atomic Energy Commission's Los Alamos laboratory began to investigate nuclear power for space propulsion. Although a few small, prototype engines were tested at a Nevada test site and NASA built several new facilities at Plum Brook to support the program, it was canceled in 1973, before the new Ohio facilities could host any nuclear testing.

While Plum Brook may have been best known for its reactor, Glenn engineers also built facilities there to perform a variety of tests that involved extreme conditions and/or a greater-than-normal safety risk. Having seen the location's potential for such facilities, NASA began incrementally purchasing additional portions of the site, and it owned the remaining 8,500 acres by 1963. With this large area, it was possible to build each of these high-risk facilities well away from the others. In some cases, such as the Space Propulsion Research Facility and Hypersonic Tunnel Facility, even their control rooms were located a quarter of a mile away to protect operators from potentially catastrophic accidents during tests.

Budget limitations during the post-Apollo era meant that most long-range space-exploration work was discontinued, including the programs at Plum Brook. Following an orderly shutdown process, the entire station was placed in mothball status in 1974, and it remained in this status until 1987, when NASA and potential users began to look at reopening a few of Plum Brook's unique facilities, including the Space Power Facility, Spacecraft Propulsion Research Facility, and Hypersonic Tunnel Facility. The first two have reopened and are currently in service. In 2006, the Hypersonic Tunnel Facility was placed in a deep standby status.

Only two of the widely separated facilities at Glenn's Armstrong Test Facility are visible in this 1999 photograph, the Space Propulsion Research Facility in the foreground and the Hypersonic Tunnel Facility at the upper left. (Photo credit: NASA GRC-1999-C-02306)

ALTITUDE WIND TUNNEL

This 1955 aerial view of the Altitude Wind Tunnel shows the tunnel and its connections to the Engine Research Building in the foreground, along with the Refrigeration Building and cooling tower at the upper right and a portion of the Exhauster Building at left. The Icing Research Tunnel is visible at the upper left. (Photo credit: NASA GRC-1955-C-38784)

SIGNIFICANCE

The Altitude Wind Tunnel (AWT) was the first wind tunnel constructed at the NACA's Aircraft Engine Research Laboratory (AERL), now known as NASA's Glenn Research Center, and it was the nation's first tunnel to combine a large size, high speed, temperature control, and pressure control, resulting in the first facility capable of testing full-scale power plants in conditions comparable to actual flight. Although designed to test large piston engines and propellers, the AWT tested America's first jet engine and airplane, as well as other jet and turboprop engines, during the late 1940s and 1950s.

The AWT also served as a test platform for the Project Mercury escape tower, and it provided space for a multi-axis chair used to train Mercury astronauts. During the early 1960s, the AWT was modified into a low-pressure facility to test Centaur upper-stage booster rockets and spacecraft shroud separations in a simulated space environment. Renamed the Space Power Chambers (SPC), the facility was an excellent example of adaptive reuse by NASA.

DESCRIPTION

The AWT was a large, closed-circuit, subsonic wind tunnel with a 20-foot-diameter test section, but it had a unique combination of refrigeration, pressure control, and

air-handling systems that gave it unprecedented capabilities for testing operating engines and made it the most complex tunnel built at that time. The footprint of the tunnel itself occupied only about half of the area needed for the entire complex, which included a makeup air dryer, refrigeration plant and cooling tower, air heater, and two exhauster buildings in addition to the shop/office structure and tunnel circuit. These auxiliary buildings were primarily brick with steel frames. The portion of the Shop and Office Building that housed the test section was sheathed with metal panels. Except for the cooling tower and a later addition to the Shop and Office Building, these structures featured substantial areas of windows.

The tunnel shell was fabricated from 1-inch-thick high-strength copper-nickel steel plate, with all joints welded airtight, and the circuit measured approximately 263 by 121 feet overall. Its four corners were equipped with turning vanes whose elliptical support rings also served as the major structural elements for the corners of the tunnel. These and eight circular rings spaced throughout the straight sections transferred the tunnel's weight to steel legs and concrete pedestals. All except one pair of anchor legs were provided with rollers to accommodate the tunnel's thermal expansion and contraction, which could approach 5 inches at the west end. The remaining pair anchored the tunnel in position. Additional, smaller rings at 6-foot intervals stiffened the pressure shell, which was designed for internal operating pressures from 1.5 to 14.7 psia, the former being equivalent to an altitude of 55,000 feet. From the 20-foot-diameter test section, the tunnel's diameter gradually enlarged to 27 feet at Corner 1, 31 feet at Corner 2, and finally 51 feet from Corner 3 through the settling chamber after Corner 4. The AWT's centerline was approximately 28 feet above the ground level. The circuit was externally insulated with a 1- to 2-foot-thick air space and a 4-inch-thick glass wool blanket covered with a steel jacket.[2]

The AWT's test section measured 40 feet in length, and a hinged door that furnished access for installing test articles formed its top half. A custom hoist opened and closed the door, and a 10-ton overhead bridge crane handled the lifts of test articles. The test section's 20-foot diameter had been dictated by the need to test the largest propellers envisioned. A variety of mounting arrangements were available, with many engine tests utilizing the airplane's fuselage or nacelle with the wings trimmed to span the test section, where they were secured with wall mounting hardware. Unshrouded jet engines and engines with propellers could also be mounted and operated using floor-standing or spanwise trunnion mounts. Initially, a six-component balance in a sealed chamber beneath the floor measured forces and moments from either mounting arrangement, though smaller strain gages largely replaced it during the 1950s. The balance's scales had printers that enabled an operator to press one button and initiate simultaneous printing of their loads on paper tapes. An exhaust scoop captured the engine's exhaust gases, which were then extracted by a large exhauster system. Dried makeup air was introduced in the settling chamber to replace the exhausted gas. Operating pressure

(vacuum) inside the tunnel was maintained by controlling the relative volumes handled by the makeup and exhaust systems.

The AWT's prime mover was a General Electric 18,000-horsepower induction motor with a modified Kramer speed control. This motor was located in a cupola on top of the exhauster building's southwest corner, and a drive shaft from it penetrated the tunnel's Corner 2, passed through the turning vanes, and entered the nose of a streamlined nacelle that contained the fan. In accordance with standard practice of the time, the 12 fan blades were fabricated from Sitka spruce and interlocked to form a solid hub. The variable-speed motor turned the 31-foot-diameter fan at speeds of up to 410 revolutions per minute to produce test air speeds of up to approximately 425 miles per hour.[3] The Kramer control system's dual motor-generator sets and Amplidyne generator occupied space below the motor on the first floor of the Exhauster Building. The Kramer system was shared with the Icing Research Tunnel (IRT) until 1986.

The original exhauster system consisted of four Worthington 30- by 60-inch reciprocating pumps that occupied most of the high-bay first floor of the Exhauster Building, which was located on the AWT's east side. Each pump had four cylinders and was powered by a 1,750-horsepower motor. These pumps drew air through the exhaust scoop to remove combustion products and partially evacuate the tunnel to simulate altitudes as high as 55,000 feet and exhausted to the atmosphere. The introduction of jet engine testing demanded increased exhauster capability to handle the greater volume of exhaust gases these engines produce compared to piston engines. Accordingly, an upgrade project in 1951 added a second exhauster building containing three 2,000-horsepower Ingersoll-Rand eight-cylinder reciprocating pumps. These pumps operated in parallel with the Worthington pumps. To further increase the exhausting capacity, the upgrade project included a 6-foot-diameter overhead duct connection across Ames Road to the Engine Research Building (ERB), where it joined that laboratory's central exhaust system. A gas cooler was also added to spray water on the hot exhaust gas coming from the scoop. Cooling the hot gas increased its density and maximized the exhauster system's efficiency.

To simulate the low temperatures encountered at high altitudes, the AWT was equipped with a large refrigeration system that could maintain the tunnel's air temperature as low as –47°F. Achieving this involved the installation of one of the largest refrigeration systems installed up to that time. A refrigeration building on the AWT's west side housed 14 Carrier centrifugal chillers rated at 500 tons (6 million British thermal units per hour) each. Each chiller was driven by a 1,500-horsepower motor. These chillers, which employed dichlorodifluoromethane (CCl_2F_2), or R-12, supplied the refrigerant to direct-expansion cooling coils located in the tunnel's west leg. To achieve the required surface area, the coils were arranged in an accordion-like manner. This refrigeration plant also served the IRT that was built just south of the AWT and opened about a year after it. Given the huge size of this system and the NACA engineers' lack of experience with air conditioning, Willis Carrier, a refrigeration pioneer

and founder of the company that bears his name, personally attended to the major design calculations and details.

Atmospheric makeup air was conditioned by a combination refrigeration-adsorption unit that cooled incoming air to reduce its moisture content to 0.005 pounds of water per pound of dry air. This system also used R-12 refrigerant that was chilled by twelve 150-horsepower York reciprocating chillers in the south end of the Refrigeration Building.

Using central system connections from the ERB; a turbo-expansion chiller; or a gas-fired, indirect heater allowed combustion air to be supplied directly to the engine at any temperature between –100 and +350°F.

A large, 18-cell cooling tower fabricated primarily from redwood and able to handle 63,000 gallons of water per minute was located west of the refrigeration building. Its last two cells were added during the 1951 upgrade project. This tower served equipment within the ERB as well as the AWT and IRT systems.

The AWT's control room and data acquisition equipment were more complex than other wind tunnels of the time because of the need to control both the tunnel and the engine under test. Additionally, many engine operating parameters beyond the force, moment, and pressure data commonly needed from aerodynamic tests had to be recorded. These included engine speed, various fluid pressures, numerous temperatures, gas flows, and propeller data. Tests that required the simultaneous recording of 1,000 data channels were not uncommon. The control room was soundproofed and located adjacent to the test section, and a separate room contained the manometer panels for measuring pressures.

HISTORY

When the NACA decided to expand beyond its Langley Laboratory in 1939, the Committee decided that engine design and performance, something that heretofore had been left entirely to manufacturers, was an increasingly complex area that could well benefit from the same kind of organized research that had contributed so much to aerodynamics and airplane design. Limited work had been done at Langley over the years, but the rapidly growing size and power of new engine designs, along with the greater speed and altitude capabilities of the aircraft they powered, made it abundantly clear that research hardware designed specifically for testing engines under in-flight conditions was sorely needed.

There were, and still are, some key differences between engine and airframe testing. Models of full-scale airframes can usually be used, but only actual engines and propellers yield realistic data about propulsion. And these engines must operate under load in the tunnel, which means they must have fuel, lubricating oil, and coolant, and their exhaust gases must be extracted. The engine under test must also be fitted with sufficient instrumentation to measure myriad temperatures, pressures, forces, torques, fluid flows, vibrations, and the like, and it must be fully controllable. Engineers at Langley had pioneered some of the techniques as early as 1927 in their Propeller Research Tunnel

(PRT), but it was a low-speed, atmospheric tunnel and not capable of simulating the high speeds and altitudes commonly being reached a dozen years later.

Initial plans for the AERL, the first designation for what became the Lewis Flight Propulsion Laboratory and is now NASA's Glenn Research Center, centered on three primary facilities: the ERB housing various component and fuel laboratories and engine static test cells; the Engine Propeller Research Building (EPRB); and the Engine Research Tunnel (ERT), soon named the AWT, although the tunnel was the subject of intense debate before it was included and funded by Congress. Engine builders and some within the NACA believed the tunnel would usurp the builders' historic development role and contribute little, if anything, to fundamental research.

On the other hand, General Henry H. "Hap" Arnold, chief of the United States Army Air Forces (USAAF), argued strongly for its construction, as did NACA Power Plants Committee Chairman George Mead. Unlike the manufacturers, Arnold had witnessed how German research facilities had improved its engines, and he passionately felt that dynamic testing in a flight environment would lead to similar improvements in engines for the USAAF without the cost and risk of extensive flight-testing. With previous engineering and executive experience at Wright Aeronautical and Pratt & Whitney, America's two largest aircraft engine manufacturers, Mead well understood the difference between the "development" of specific engines and "research" that the NACA could do for the benefit of all engine builders and suppliers. The position of Arnold and Mead prevailed with the NACA's Executive Committee, and ultimately with Congress, which included funding for the AWT in its 1940 appropriation for the AERL. Still not convinced of the AWT's usefulness or appropriateness, the engine manufacturers persisted in their objections even after the tunnel entered service.[4]

As with the Ames Laboratory, key personnel for the Cleveland laboratory, including E. Raymond Sharp, who served as the laboratory's director through 1960, and Charles Herrmann, the NACA's chief construction inspector, transferred from Langley in 1941 to manage the construction and start-up efforts. But the NACA appointed Mead to lead the team that designed the initial parts of the AERL. Using Mead's specifications, engineers at the NACA's Langley Laboratory, led by Alfred W. Young and Larry Marcus, designed most of the facility except the tunnel itself, including the makeup and exhaust systems, test chamber, control room, fan blades, and support buildings. The difficult task of designing the tunnel to be aerodynamically efficient while enduring the stresses posed by the unprecedented combination of large temperature and pressure excursions Mead wanted fell to another team of engineers at the Ames Laboratory led by Carlton Bioletti. Walter Vincenti performed most of the structural analysis. Designing such a large vessel for low-temperature and pressure service involved plate theory that was relatively new at the time, and Vincenti, who had studied under Stephen Timoshenko, a renowned Stanford University professor and pioneer in the field, secured his assistance to ensure that the stress calculations were correct. Bioletti worked with General

Electric engineers to design the tunnel's drive, and the role of Willis Carrier has already been noted.[5]

In spite of the wartime difficulties in purchasing the high-strength steel needed to withstand the inward pressure and cold temperature, AWT construction began in mid-1942, with the Pittsburgh–Des Moines Steel Company serving as the fabricator and erector. The complex tunnel officially opened in May 1944, but its first tests were actually run secretly in February, when a Bell YP-59A Airacomet, a preproduction model of America's first turbojet-powered plane, was clandestinely mounted—without wingtips—in the AWT's test section for tests of its two General Electric I-16 engines. The first "official" test program involved the trouble-plagued Wright R-3350 radial piston engine developed for the Boeing B-29 Superfortress bomber, and these tests revealed practical solutions to the engine's notorious overheating problems. But the I-16 jet engines were the harbinger of things to come, and the AWT saw only three additional piston-engine tests during its service life.[6]

Since the AWT had been designed around the requirements of large piston engines and propellers, it was less than ideal for jet engine testing. In a turbojet, all of the propulsion air flows through the engine and exits as contaminated exhaust, unlike a piston engine that uses relatively little air for combustion and uses its propeller to generate thrust with clean air. This meant that the exhauster and makeup-air systems were overloaded and that the tunnel's maximum speed was less than desirable.

A four-month modernization program completed in September 1951 added equipment to address these problems. The new equipment included an 18-blade controllable-pitch fan, three exhauster pumps, additional combustion air supply units, two cooling tower cells, and a connection to the laboratory's central exhaust system. Within two years, a turbo-expansion cooler for combustion air was installed, along with an improved engine fuel supply system. An earlier project had installed mufflers on the exhauster system in response to noise complaints from neighbors.[7]

Engineers at Lewis realized that the refrigeration and air-handling abilities of the AWT could support other facilities when the tunnel did not need them, and they soon began building other wind tunnels close by to explore other areas of interest. The IRT shared the refrigeration plant, but the AWT's auxiliaries also supported a set of three small supersonic tunnels (often called the Stack Tunnels) and another 4- by 10-inch supersonic tunnel known as the Duct Lab. The 8-foot-long Duct Lab, located in a basement corridor, utilized the AWT's exhaust pumps to produce speeds between Mach 1.6 and 5.0, and it was equipped with a schlieren system. A laser anemometry system was added later for flow visualization, as was a system to measure Rayleigh scattering[8] in supersonic flow. Installed in 1945, the Duct Lab remained in service for many years after the AWT closed, using the center's vacuum system as its power source. Initially used mainly for engine inlet studies, it was utilized for supersonic injector testing, laser systems development, and advanced flow physics studies for almost two decades until it was closed in 2007.[9]

The AWT continued in active service until February 1958 testing a variety of engines, and test programs it hosted involved jets, turboprops, ramjets, and rockets, as well as related devices such as afterburners and noise suppressors. By 1958, however, other tunnels had been built at Lewis, including the Propulsion Systems Laboratory and the 10- by 10-Foot Unitary Plan Wind Tunnel, that could produce considerably better conditions for testing jet engines than the AWT. Except a brief series of small rocket tests during 1958–59, the AWT sat unused.

While the AWT's days as a wind tunnel were over, the facility did not stay unused for long. The Soviet Union's launch of Sputnik on 4 October 1957 propelled the United States into what became known as the space race with the Soviet Union, with the next big goal being a man in orbit. Project Mercury, America's man-in-space program, quickly began looking for ways to develop the necessary hardware and train the first seven astronauts, and the unused AWT could at least provide some badly needed space in short order. The cooling coils, as well as the turning vanes in Corners 3 and 4, were removed, and appliances were installed overhead from which a Mercury capsule and the top portion of a Redstone or Atlas booster rocket were hung. The arrangement allowed full-scale testing of the devices that would separate the two under high-altitude conditions. Similar tests evaluated the separation performance of the capsule's launch escape tower.[10]

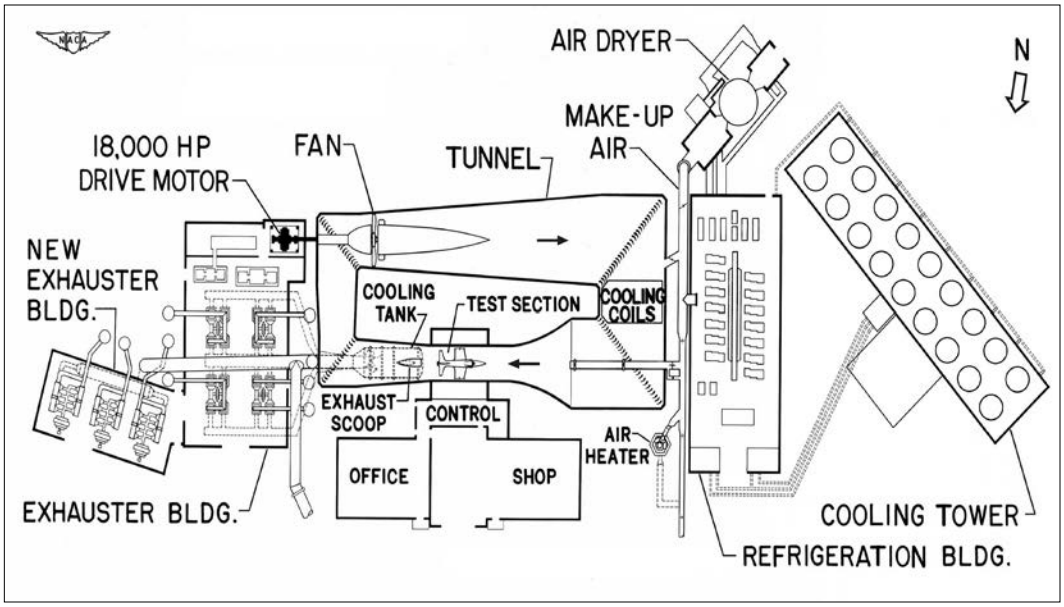
Another part of the Mercury capsule development involved its control system, which had to stabilize the capsule from any conceivable combination of motions. To test the control system, Lewis engineers David Gabriel, Louis Corpas, and Frank Stenger designed and built the large Multiple Axis Space Test Inertia Facility (MASTIF) in the western end of the AWT. Simultaneously, William Fleming led a team that checked the tunnel's shell, rewelding much of it in the process, and made it suitable for simulating altitudes as high as 80,000 feet. The MASTIF consisted of three concentric frames with gimbaled joints that allowed complete freedom of rotation about all three axes. Air jets set the MASTIF in motion with the capsule mounted at its center, and the capsule's control system had to fire its reaction jets to achieve stability and the proper orientation. Begun in spring 1959, these control system test programs were well under way within a year. Following the control system tests, Lewis engineer James W. Useller installed a seat and controls in the MASTIF, renamed the Gimbal Rig, so it could be used to evaluate how astronauts responded to multi-axis motion and to teach them how to stabilize the capsule manually. All seven Mercury astronauts spent time in the Gimbal Rig during early 1960.[11]

The AWT had proven its usefulness as a high-altitude chamber with Project Mercury, so when Lewis engineers needed a vacuum chamber for another project in 1962, they looked at modifying the tunnel again. These engineers had been working with Pratt & Whitney and Convair since 1956 to develop the RL-10 hydrogen-fueled rocket engine and the Centaur upper-stage booster to use it. By 1961, they needed a way to test its systems in a high-vacuum environment before flight. This was essential because the

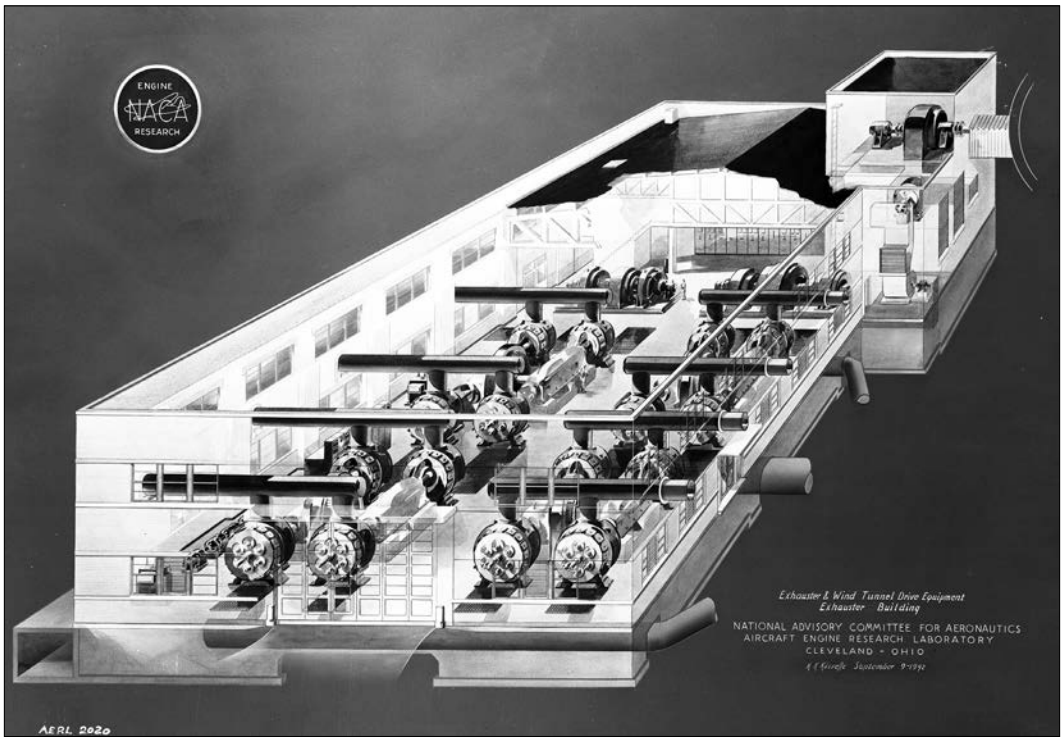
Centaur was to be restartable in space, something that had never been done with hydrogen fuel. Engineers rebuilt the AWT's east end into a high-vacuum chamber by removing the fan and installing elliptical bulkheads near Corners 1 and 2. All of the insulation was removed and a 22.5-foot-diameter, dome-shaped hatch was installed on top of the shell near Corner 2. Ten oil-diffusion pumps were installed to produce and maintain pressures down to 0.0001 millimeters of mercury (0.000001.9 psia). The resulting Chamber Number 1 measured approximately 100 feet long by 30 feet in diameter. As part of this project, a third bulkhead was inserted near the old test section nozzle to allow the west end to function as a separate high-altitude chamber, Chamber Number 2, to simulate altitudes of up to 100,000 feet. Lewis's Central Process System could evacuate it adequately, so the AWT's seven exhauster pumps were removed and sold. The useful portion of Chamber Number 2 was 121 feet long and 50 feet in diameter. The reconfigured facility was renamed the Space Power Chambers when it opened in September 1962.[12]

The SPC served as NASA's main high-vacuum chamber test facility until the Space Power Facility (SPF) at the Plum Brook Station opened in 1969. Managed by the Lewis Center, the SPF's larger size and better ability to simulate the vacuum and temperatures of deep space rendered the SPC increasingly obsolete, and it hosted its last test in 1975. During the 1980s, an extensive study at Lewis recommended that the facility be rebuilt once again, this time into a Propulsion Wind Tunnel with more power, a slotted test section, a second low-speed test section for helicopter rotors, and enhanced icing research capabilities. Early cost estimates ranged between $75 and $160 million, depending on several options. While this proposal was strongly advocated by a broad spectrum of the aviation community and would have produced a very capable, modern tunnel as early as the mid-1980s, it came at a time when NASA budgets were under pressure from Congress. With most of the proposed capabilities already existing to some degree elsewhere, NASA management did not approve the project.[13]

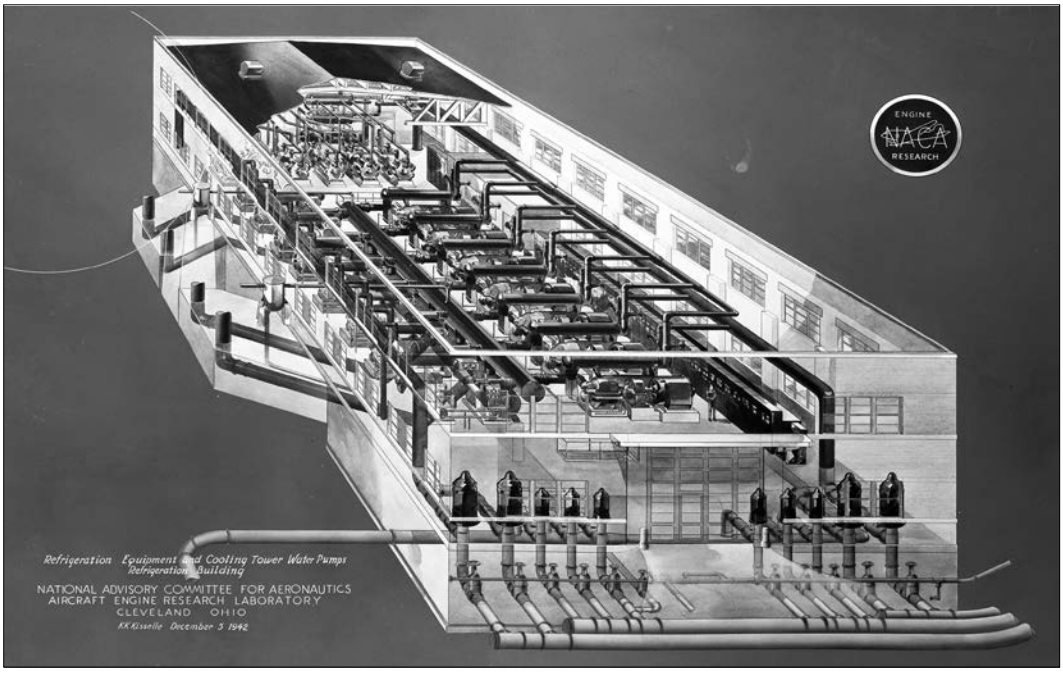
NASA's budget pressures continued to increase, and in 2003 the agency decided to reduce maintenance costs by demolishing closed facilities. The AWT/SPC was one of these facilities, and it was approved for demolition in 2005. Because of the historical significance of this facility, NASA produced an extensive documentation package for it before proceeding with its demolition in 2009.[14] The steel AWT/SPC shell and Duct Lab were removed, but most of the complex's buildings were in use by other activities, and they remain in place. The refrigeration plant still serves the IRT and the ERB, and the exhauster buildings served as an educational center until 2009. The office and high-bay shop building, including much of the AWT's original test section, also remains in place. It has been used in recent years as an antenna research facility.[15]



This schematic drawing of the Altitude Wind Tunnel includes internal tunnel components such as the exhaust scoop and fan, as well as the six support buildings. (Image credit: NASA CD-07-83009)

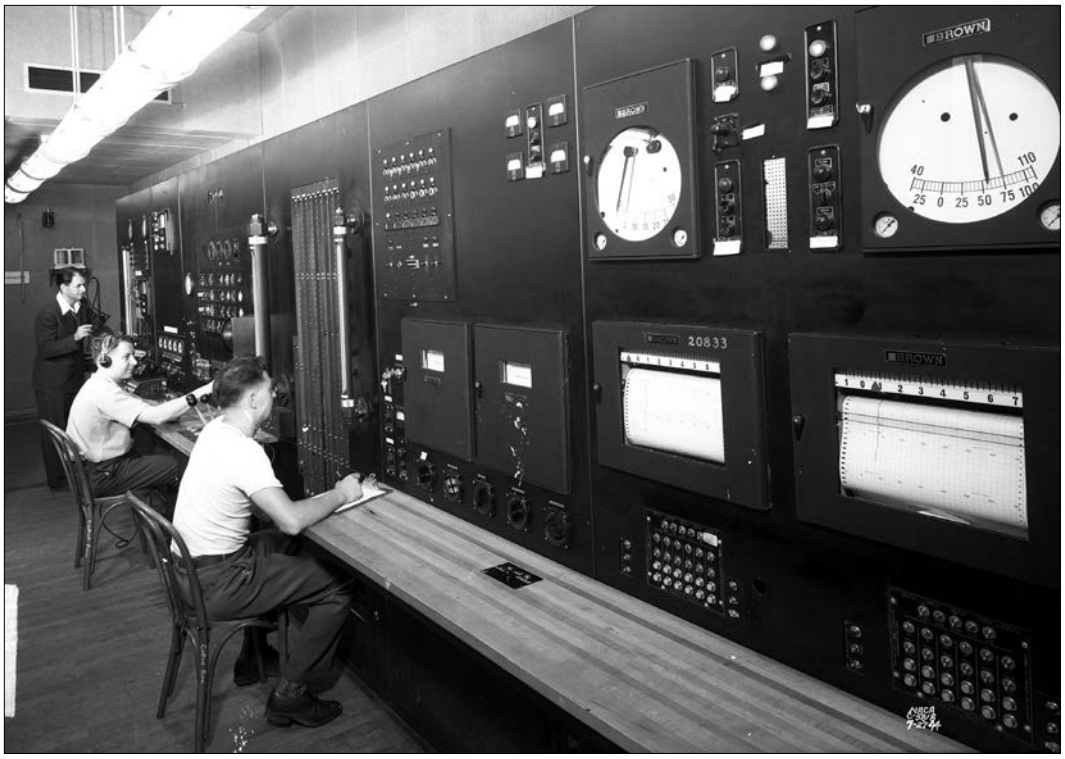


This 1943 cutaway rendering shows the original Exhauster Building and Worthington pumps. (Image credit: NASA GRC-1943-C-02020)

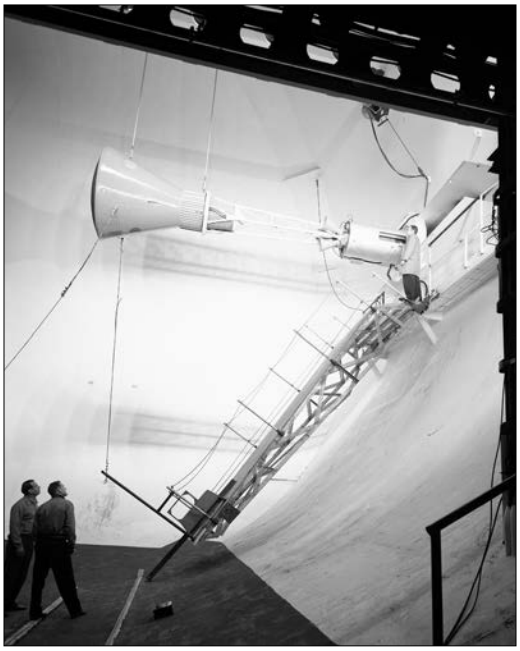


Fourteen Carrier chillers occupied most of the Refrigeration Building. They provided 7,000 tons of cooling for the Altitude Wind Tunnel. The building also housed York makeup-air chillers and cooling tower water pumps. (Image credit: NASA GRC-1944-C-06304)

This massive cooling tower, seen here in 1944, stood about three stories high and cooled 63,000 gallons of water per minute. This water removed heat from the chillers' condensers. (Photo credit: NASA GRC-1944-C-05226)

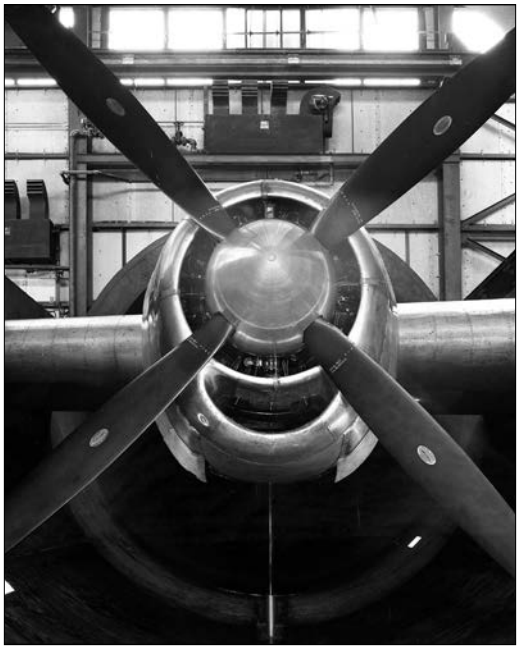


Operators at the Altitude Wind Tunnel's control panel in July 1944. (Photo credit: NASA GRC-1944-C-05818)

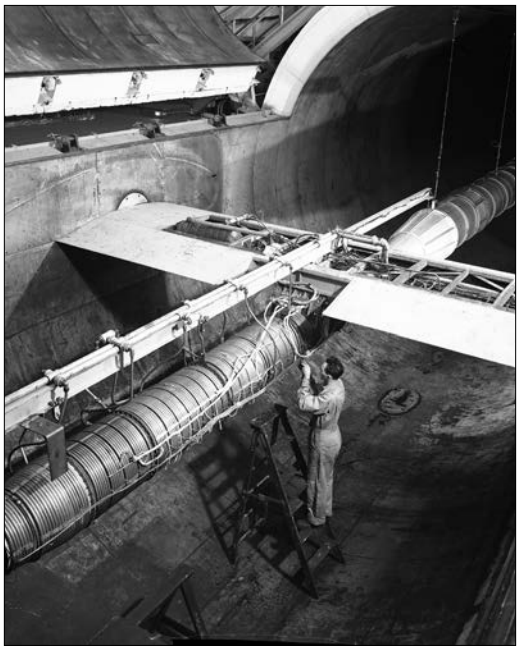


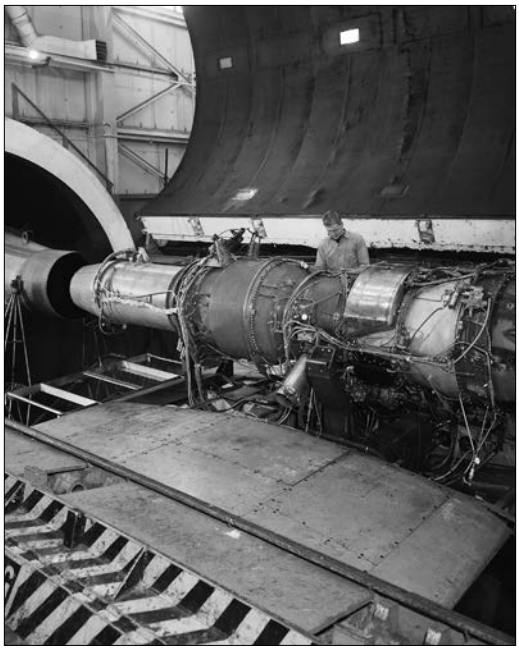
A boilerplate Mercury capsule being prepared for a launch escape tower motor test in the Altitude Wind Tunnel in 1960. (Photo credit: NASA GRC-1960-C-53286)

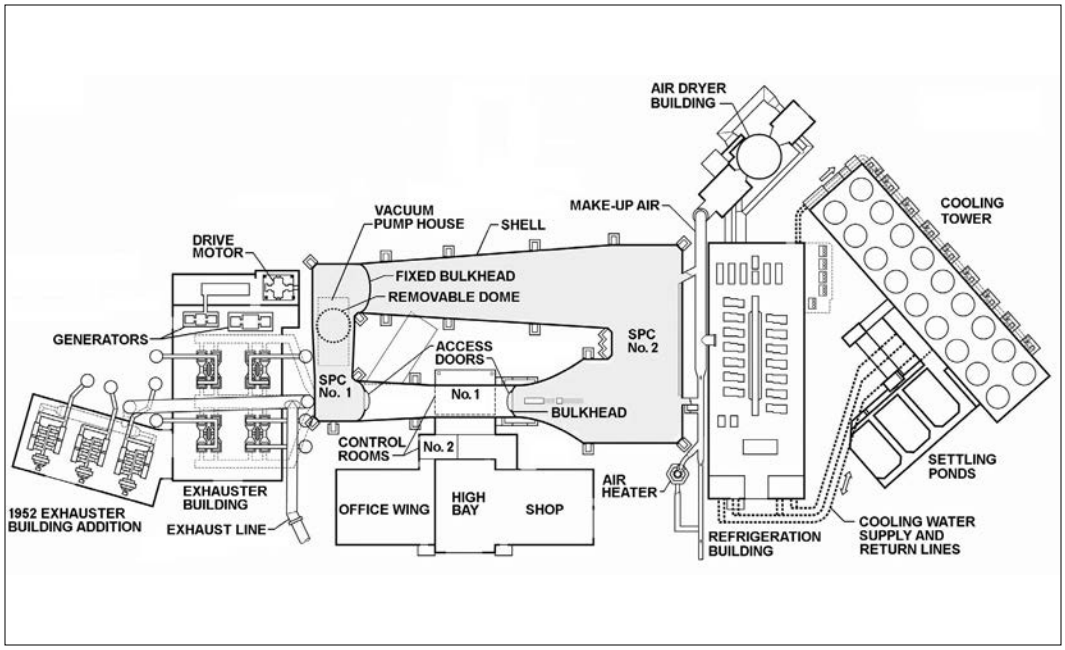
Astronaut John H. Glenn, Jr., preparing for a training ride in the Gimbal Rig in 1960. Installed in the Altitude Wind Tunnel in 1958 to test control systems, the Gimbal Rig was modified into a facility used to train all seven Mercury astronauts. In 1999, the Lewis Center was renamed to honor Glenn. (Photo credit: NASA GRC-1960-C-52739)



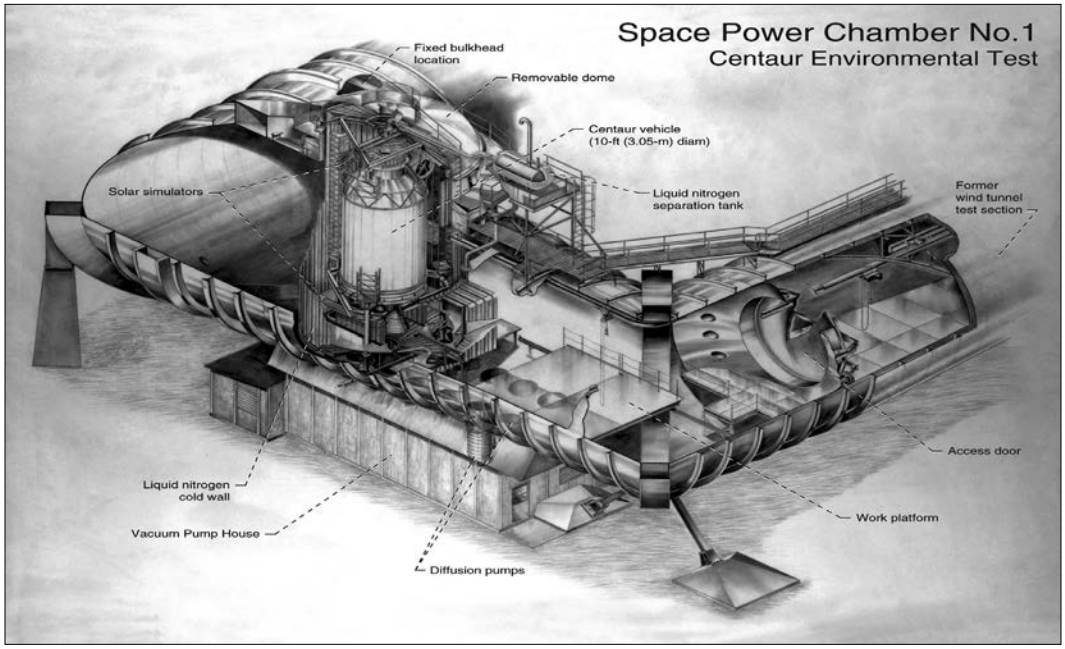
These four views illustrate the variety of engines tested in the Altitude Wind Tunnel. They are (top left) General Electric I-16 turbojets in a YP-59A, (top right) a Wright R-3350 in a B-29 nacelle, (bottom left) an NACA-designed ramjet, and (bottom right) a Pratt & Whitney J57 turbojet. The exhaust scoop is clearly visible extending into the tunnel in bottom images. (Photo credits: NASA GRC-1944-C-04825, NASA GRC-1944-C-05552, NASA GRC-1946-C-14244, NASA GRC-1954-C-34637)







This sketch shows how the Altitude Wind Tunnel was divided into two separate vacuum chambers when it was rebuilt into the Space Power Chambers. Dished bulkheads separated the spaces. The Altitude Wind Tunnel's test section was not part of either chamber. Chamber No. 2 could simulate altitudes of up to 100,000 feet. (Image credit: NASA CD-07-83009b)



In this cutaway drawing, a Centaur upper stage is shown installed for testing in the Space Power Chambers Chamber Number 1. Note the bulkhead with a large circular door to the Altitude Wind Tunnel's test section at right. (Image credit: NASA P-1047)

This aerial view shows the final configuration of the Space Power Chambers. The domed hatch on Chamber Number 1 is visible at the upper left. An electrical substation and the Icing Research Tunnel are in the background. The windowless addition in front was an expansion of the high bay for antenna testing. (Photo credit: NASA GRC-2005-C-01492)

A Centaur upper stage, equipped with two RL-10 engines, is being lowered into the Space Power Chambers' Chamber Number 1 through its domed hatch in 1964. (Photo credit: NASA GRC-1964-C-68844)

ICING RESEARCH TUNNEL

This 1945 aerial view of the Icing Research Tunnel shows the refrigeration and makeup-air structures at left and some of the refrigerant piping to the cooling coils in the tunnel. (Photo credit: NASA GRC-1945-C-13053)

SIGNIFICANCE

The Icing Research Tunnel (IRT) was the first major facility designed, built, and operated expressly for the study of ice formation on aircraft, how it creates problems, and effective means to combat it. Over the years, the tunnel not only tested numerous methods for ice protection, but it also pioneered several techniques for generating environments that accurately simulate a variety of in-flight icing conditions. It remains the foremost facility for icing research.

DESCRIPTION

The IRT is a medium-sized, closed-circuit, subsonic wind tunnel fitted with cooling coils and water spray systems to simulate a variety of environments that promote the buildup of ice on aircraft. Except for its circular fan section and transitions, the tunnel is rectangular in cross section throughout its length, and it follows the usual pattern of its cross-sectional area increasing gradually from the exit of the test section to the settling chamber ahead of the test section, where a contraction nozzle necks down to the test section dimensions. All four corners are 90-degree angles fitted with turning vanes, and the tunnel is externally insulated and jacketed throughout its length. The tunnel shell was fabricated from steel plate welded together with steel structural members that rest on concrete pedestals, and it measures approximately 198 by 75 feet overall.

The IRT is an atmospheric tunnel with an air-exchange tower built with a steel frame and corrugated asbestos-cement wall panels between the fan nacelle and Corner C.[16]

The IRT features a test section 6 feet high by 9 feet wide by 20 feet long, and a nozzle with a contraction ratio of 14:1 precedes it. Windows are fitted in both sides of the test section. They are a laminated design with an electrical resistance layer that warms the window to prevent fogging or icing. Unheated windows are in the ceiling. (Some of these windows were later removed.) Originally, models could be mounted vertically on a rotating turntable in the floor or horizontally on trunnions in the side walls. These mounting devices were connected to a six-component mechanical balance for force and moment measurement along and about the three axes. A manometer board with 298 tubes and a camera originally recorded pressures. An air purge system blew back through the connection lines and ports between tests to prevent water from freezing in them. The lines had electric heating tracers, as well. A Westinghouse distributed control system installed during a 1986–87 renovation now directs preprogrammed tests and automatically records test data directly from electric strain gages, pressure transducers, thermocouples, and other modern instruments.[17]

Within a year after the IRT opened in 1944, a second test section was developed by mounting the fuselage of a Bell P-39 Airacobra in the diffuser section, just ahead of Corner A. At this location, the tunnel measured 12 by 15 feet, making it suitable for tests of icing on propellers. A second control room in the tunnel's courtyard managed these tests. The propeller test section remained in service until early 1947, and the P-39 fuselage and supporting equipment were subsequently removed.[18]

A 4,160-horsepower wound-rotor induction motor with its speed controlled by the modified Kramer system installed for the AWT originally powered the IRT. A 5,000-horsepower induction motor with an independent, variable-frequency control system replaced the original motor in 1987. Both motors were mounted in a streamlined nacelle located in the tunnel's northern return leg. Each motor turned a 24-foot-diameter, 12-blade fan with blades of Sitka spruce that turned behind a set of stationary anti-swirl blades. The larger motor, coupled with a change in blade pitch, increased the original, continuously variable speed range of 50–300 miles per hour to 60–400 miles per hour.[19]

The IRT is a refrigerated tunnel capable of operating at temperatures as low as –35°F to simulate the full range of temperatures in which in-flight icing is known to occur. The tunnel used the Carrier refrigeration system originally constructed for the AWT, although the IRT typically required no more than 2,100 tons (25.2 million British thermal units per hour), less than one-third of the system's maximum capacity. Like the AWT, the IRT had direct-expansion coils in its west leg installed in an accordion fashion to obtain the required surface area in a reasonable volume. The original cooling coils, which had seriously deteriorated, were replaced in 1999–2000 with a pair of new, flat-face units that Boeing had developed for its icing tunnel. The modification also allowed the Glenn engineers to change the refrigerant from out-of-production dichlorodifluoromethane (CCl_2F_2), more commonly known as Freon-12 or R-12, to

tetrafluoroethane ($C_2H_2F_4$), also known as R-134a.[20] Installation of the flat-face units involved the demolition of the original 29-foot-wide west leg and its replacement with one 49 feet wide. The turning vanes in Corners C and D were also replaced with vanes that improved air distribution across the coolers and beyond into the test section.[21] In 2011, the IRT again upgraded its refrigeration system, moving beyond R-134a to R507. Included in this upgrade was the construction of a new separate facility and the replacement of the heat exchanger into horizontal banks with coils running back and forth. The fluid running through the coils is Dynalene HC-50, which is cooled in the refrigeration plant by the R507. This new heat exchanger configuration significantly improved the temperature profile within the test section.[22]

The spray system for generating the water droplets that can freeze on contact with airplane surfaces is the signature feature of the IRT. It is mounted in the tunnel's settling chamber after Corner D. Numerous designs were tried before one that employed approximately 80 spray nozzles on six horizontal bars proved that it could repeatedly deliver droplets of the small size needed. The successful spray bar and nozzle had a central tube that carried demineralized water and an annular space around that for conveying air. At each nozzle, a tube about the size of a hypodermic needle emerged from the inner tube and injected a small stream of water. Around it was an annular tube for air that extended slightly beyond the water injector. This air atomized the water effectively as the air-water combination left the nozzle through an orifice. Steam tracer lines within the streamlined fairing that covered the bar prevented freezing and ice accumulation on the bar. Additionally, a steam heater increased the water's temperature to approximately 185°F to prevent icing as it atomized leaving the nozzle. Engineers also installed a 500-gallon-per-hour demineralizer after discovering that the mineral content of Cleveland's water was sufficient to clog the nozzles. Researchers found that they could control the droplet size by regulating the water and air pressures to the spray bars. Although the droplets are not all exactly the same diameter, their mean volume diameter can be controlled to between 4 and 20 micrometers to match the natural droplets encountered in a range of icing conditions. In 1997, this system was modernized to include 540 nozzles on 10 spray bars with individual control valves on each nozzle. The new system increased the core test region with a uniform icing cloud from approximately 30 to 60 percent of the test section area. The droplet size also increased and allows for calibration of the mean volumetric diameter (MVD) from 15 micrometers up to 50 microns, but individual drop sizes as large as 160 micrometers have been generated.

HISTORY

Ice accumulation on airplanes and accidents resulting from it have been a part of aviation since its early days. By the mid-1920s, icing had begun to impose serious limits on the growth of aviation, particularly the new Air Mail Service, and especially during the winter months, when pilots flying in cold, moist air frequently experienced frost and ice buildup on their wings, tails, and even fuselages. The added weight presented a problem

for the small planes of the time, but ice changed the contour of the wings' airfoil, too, increasing drag and decreasing lift, frequently resulting in stalls and crashes. Carburetor icing and subsequent engine failures only worsened their problems. Aviators understood that flying through clouds could be particularly hazardous, but no one understood exactly what the icing mechanism was, or what, if anything, could be done about it.

It was a problem that seemed to be tailor-made for the NACA, and researchers at the Langley Laboratory were among the first to investigate it, building a 6-inch closed-circuit wind tunnel with a nozzle to spray chilled water into the airstream in 1928. The little tunnel suffered from not having a nozzle that could produce realistically small droplets, but it did cause ice to accumulate on a model wing, and it allowed researchers to try a variety of coatings—from soap to goose grease—to see if they might help prevent ice from forming, but none had a significant effect, and Langley abandoned the tunnel in 1935. Three years later, Langley received funds to build an icing tunnel, but the tunnel Eastman Jacobs built ran only one rudimentary series of icing tests before he removed the refrigeration and insulation to use it for other purposes.[23]

While various flight-test programs developed some information on the subject, including that there were two different types of ice, glaze and rime, that formed at different temperatures and in different shapes, the engineers at Langley believed they had shown that a plane's engines generated enough heat to prevent ice buildup; it was now up to the manufacturers to design systems to distribute that heat. Outside the agency, Army, Navy, and civil aviation group leaders still believed that the problem was far from being solved, and they pressed for a serious research program.[24]

While the NACA's decision to build the IRT at the Aircraft Engine Research Laboratory (AERL) instead of either of its two aeronautically focused laboratories might seem odd, one simple fact dominated the choice. Large air-conditioning systems were rare and expensive in the early 1940s, but the huge refrigeration plant that Carrier was building for the AWT would have more than enough cooling capacity for the IRT's demands. Having the two tunnels share the refrigeration plant saved considerable construction time, money, and materials that were needed for other wartime projects. Notes from a February 1942 conference of three Langley engineers imply that the decision had been made by then, and that their responsibility was only to write the tunnel's specifications. With differing opinions on the merits of such a tunnel, John W. Crowley, Jr., Carleton Kemper, and Robert T. Jones finally recommended that the "Cleveland Ice Tunnel" be essentially a duplicate of the two new 7- by 10-foot aerodynamic tunnels being built at the Ames Laboratory with insulation and cooling down to –20°F. They fully expected that, like Langley's Icing Tunnel, the IRT would end up performing aerodynamic, not icing, tests.[25]

At the AERL, two engineers, Alfred W. Young and Charles N. Zelenko, were primarily responsible for the IRT. Young and Zelenko worked for Design Group Head Ernest G. Whitney, who reported to Construction Manager E. Raymond Sharp. Unlike the Langley team, they looked first at the requirements for an ice-producing water spray,

rather than the tunnel's aerodynamic capabilities, and they concluded that a 6- by 9-foot tunnel would be more suitable. It would reduce the construction cost by 15 percent and cut the ongoing power bills in half. Their analysis, in consultation with the refrigeration system supplier Carrier, indicated that a direct-expansion coil similar to the one designed for the AWT would maintain the tunnel's temperature at –40°F or lower.[26]

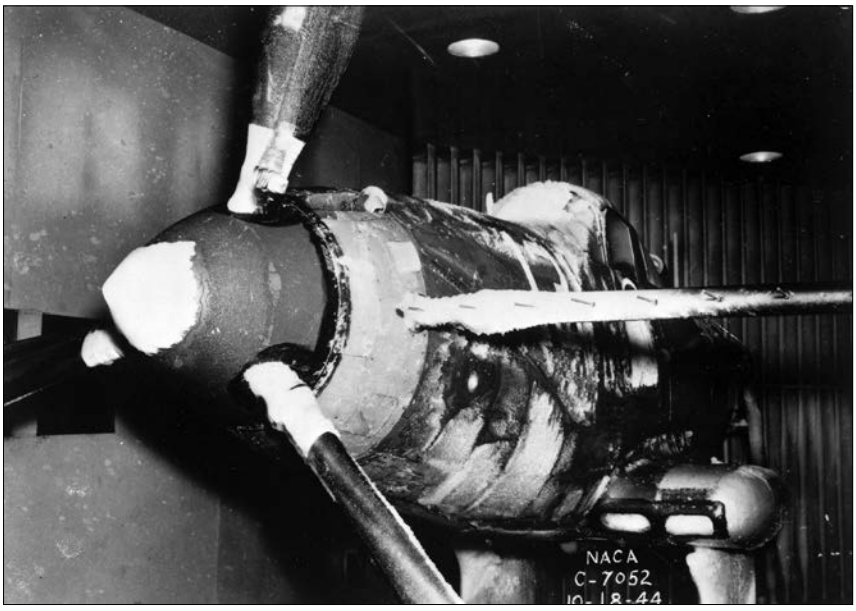
With speed a priority during World War II, the AERL contracted with the Pittsburgh–Des Moines Steel Company to build both the AWT and the IRT simultaneously, and construction began in mid-1942. As with the AWT, the contractor's most serious problems involved materials procurement, but after receiving a higher priority from the War Department, construction proceeded smoothly, and the IRT was completed in March 1944.

The truly open-ended issue involved the spray system. Previous experience and research offered almost nothing useful, except for some guidance in what not to do. In mid-1943, the NACA hired Wilson H. Hunter, an engineer with considerable experience in icing, and assigned him to work with another AERL engineer, Halbert E. Whitaker, to design the IRT's spray system. Their first design, employed at the IRT's start-up, used water nozzles with a 0.01-inch gap and air nozzles behind them. These were installed on a rotating bar mounted on a post in the settling chamber. Operators had to determine the air- and water-pressure settings for each nozzle individually. Unfortunately, problems abounded. The spray cloud was concentrated in the center of the test section. Replacing the nozzles with commercially available ones produced a better distribution, but the droplets were much too large. A demineralizer had to be installed to reduce nozzle plugging, and different plumbing materials caused galvanic corrosion, necessitating a wholesale replacement.

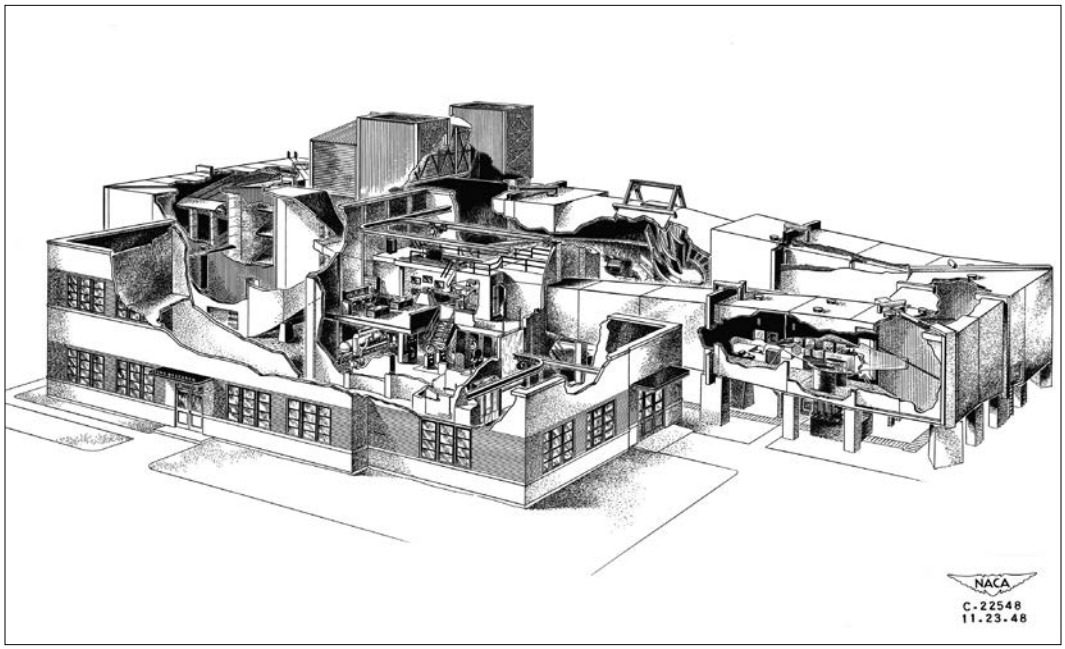
Even as these problems were slowly being addressed, calibration of the IRT continued, and its first actual test occurred in August 1944. Progress came to an abrupt halt on 29 December when the main drive motor suffered an explosion. An investigation determined that overheating had caused some of the insulation to emit flammable fumes that were ignited by an arc from a short circuit resulting from the failed insulation. Fortunately, no one was seriously injured, but the tunnel was out of service for two months until a new motor could be installed, along with some additional safety provisions.[27]

In 1946, the NACA decided to consolidate its icing research at what was now the Lewis Flight Propulsion Laboratory, and it relocated a flight-based program at Ames to Cleveland. The move proved fruitful, as the IRT work and flight-testing complemented each other. Historian William Leary has aptly referred to the next six years as "a golden age" for Lewis's icing research program, because this period witnessed a tremendous growth in icing knowledge and the development of effective anti-icing systems, particularly for jet aircraft and nacelles. Tests in the IRT also examined changes in performance and handling due to ice accretion, and they identified performance penalties for radar systems within ice-encrusted radomes.[28]

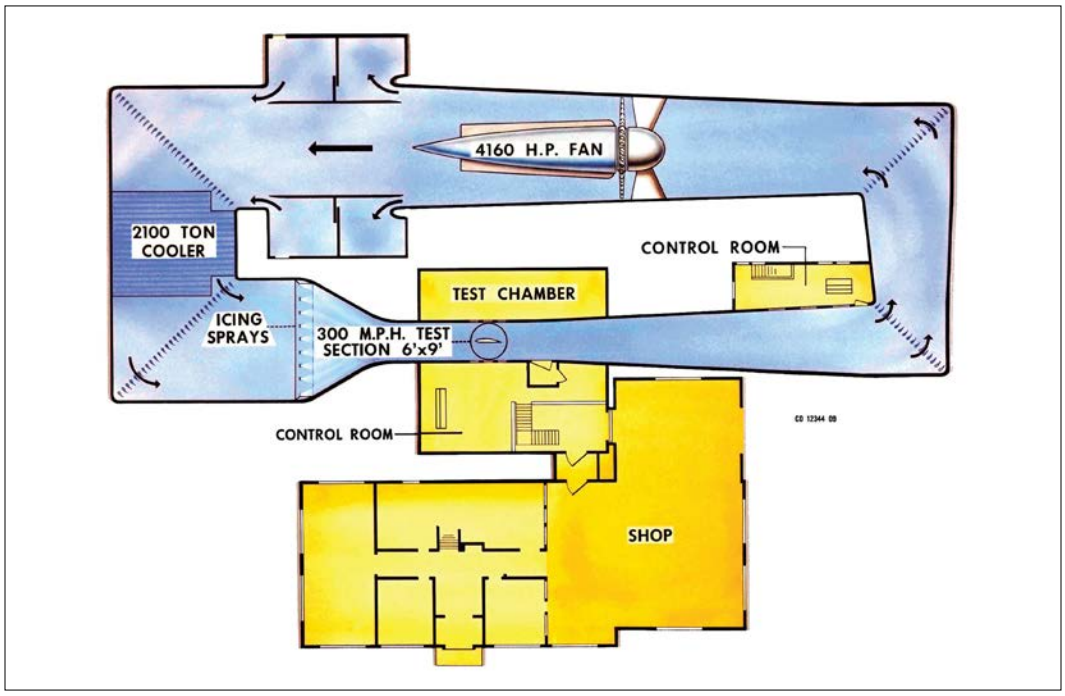
Testing in the IRT fell dramatically after 1956, as the Icing Section's accomplishments caused many, including much of the section's staff, to believe that the fundamental problems of icing had been solved, leaving only engineering design challenges for new aircraft. Consequently, when NASA subsumed the NACA into the new agency in 1958, these staff members were assigned to other areas, and most expected that the IRT would soon be demolished. Industry interest in the IRT, however, had not waned, though it had changed somewhat, and companies still wanted to test in the tunnel. Particularly interested were helicopter manufacturers. Helicopters had matured during the 1950s, but more-demanding requirements had made rotor icing a major issue. Other advances in aviation during the 1960s and 1970s, including the introduction of wide-body transports, business jets, and supercritical wings, increased the need to test new deicing systems. The demand eventually forced NASA to reinstitute the icing research program at Lewis in 1978, and studies were soon under way to define the needed facility improvements. The AWT was considered for rebuilding into a super icing tunnel, but that was rejected due to its excessive cost, and the IRT retained its place in icing research. Tunnel bookings to test a variety of new helicopters, airplanes, and deicing systems increased during the 1980s, and the IRT's age and wear began to cause problems. Renovation and modernization projects in 1986–87, 1996–97, and 1999–2000 have upgraded the tunnel's performance and reliability. As the IRT was coming back online after the first of these projects, the American Society of Mechanical Engineers recognized it as an International Historic Mechanical Engineering Landmark, noting both its role in improving aviation safety and the innovative refrigeration and spray technology that made it possible. The IRT remains in active service, and it is currently the most-heavily booked tunnel at Glenn Research Center.[29]



A P-39 Airacobra fuselage and engine installed in the Icing Research Tunnel's diffuser supported propeller icing tests between 1944 and 1947. (Photo credit: NASA GRC-1944-C-07052)



Though not labeled, this cutaway drawing reveals most of the Icing Research Tunnel's main components, including the cooling coils, the first rotating spray bar, the control room next to the test section, and the fan. A phantom image of the P-39 propeller test rig can also be seen at right. (Image credit: NASA GRC-1948-C-22548)



This plan drawing locates the Icing Research Tunnel's major features. The refrigeration building that serves the cooling coils (not shown) is located to the upper left. (Image credit: NASA CD-1234409)

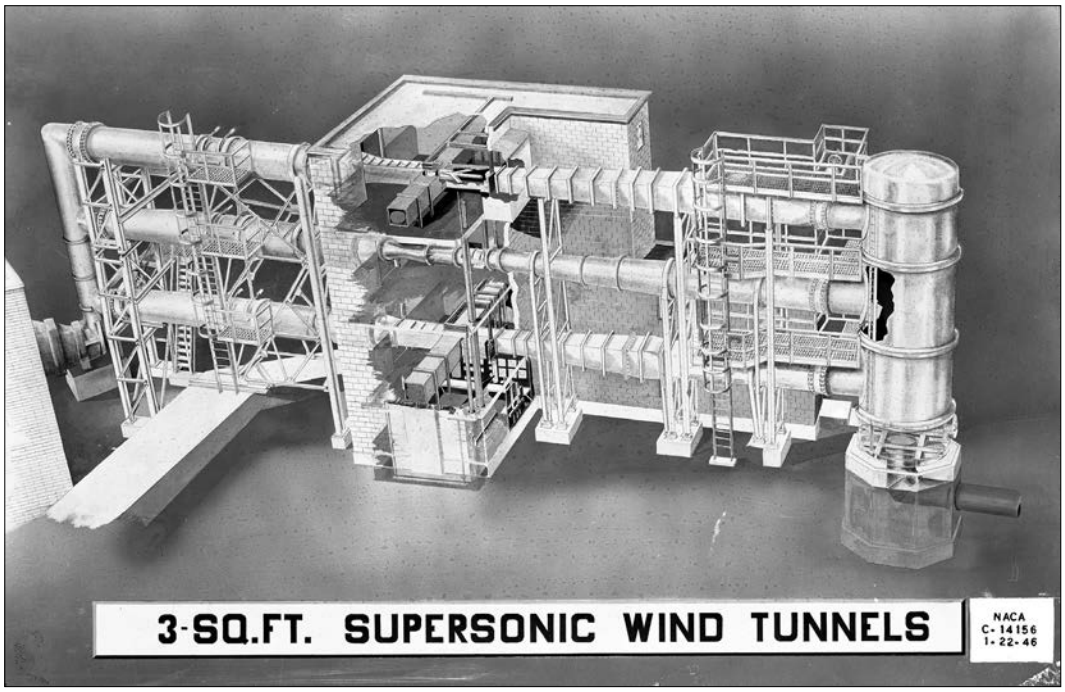
This rotating arm, seen here in 1944, was the first attempt at generating a cloud of water droplets in the Icing Research Tunnel. It was not successful. (Photo credit: NASA GRC-1944-C-05312)

This arrangement of six horizontal bars with about 80 nozzles produced the small droplets needed, and it served the Icing Research Tunnel for 46 years. (Photo credit: NASA GRC-1950-C-26482)

A researcher examines the results of an airfoil icing test in the Icing Research Tunnel's main test section in 1969. (Photo credit: NASA GRC-1969-C-00503)

A researcher examines the ice buildup on a turboprop engine nacelle in 1983. The nacelle was mounted on its side to center it in the optimum cloud field. (Photo credit: NASA GRC-1983-C-01156)

SMALL SUPERSONIC TUNNELS



This 1946 cutaway rendering shows the SSTs as they would be in 1949, with three tunnels in the building and the exhaust manifold at right. The inlet connection from the makeup air dryer is on the left. The Altitude Wind Tunnel's exhausters furnished draft for the SSTs. (Image credit: NASA GRC-1946-C-14156)

SIGNIFICANCE

The Small Supersonic Tunnels (SSTs) were a group of three small tunnels that provided researchers at Lewis with their first supersonic facilities. By utilizing the AWT's makeup and exhauster systems as their power source, these tunnels were built quickly and inexpensively, and they proved to be valuable tools for early supersonic research until more complex and capable tunnels could be built, as well as for preliminary testing after that.

DESCRIPTION

The SSTs, also known as the 3-Square Foot Supersonic Tunnels[30] or simply the Stack Tunnels, were a group of three small tunnels in an L-shaped masonry structure between the AWT and IRT. Because of space limitations and the necessity of being close to the AWT's makeup and exhauster facilities, the three horizontal tunnels were "stacked" in a three-story structure. Each of the test chambers measured approximately 12 by 30 feet in plan.[31]

The building's ground floor, whose floor level was actually below grade, housed a control room that managed all of the tunnels. Tunnel Number 1, the 18- by 18-inch tunnel, was built on the second floor, with 20-inch-diameter Tunnel Number 2 on the third floor. Tunnel Number 3, built in 1949, occupied a fourth-floor addition to the

building. In 1951, Tunnel Number 2 was modified into a 24- by 24-inch square tunnel. While the first two tunnels were originally designed for a nominal speed of Mach 2, additional nozzles were fabricated that allowed them to run at several speeds between Mach 1.4 and 2.2. Tunnel Number 3 operated between Mach 3.0 and 4.5, while the second Tunnel Number 2 ran at Mach 3.05.

Only one of these tunnels operated at a time. They were powered by draft from the AWT's exhauster pumps, initially through the AWT via connections to its shell, and later by an underground pipe from a vertical manifold to the exhauster building. Inlet air for the SSTs passed through the AWT's makeup air dryer, a vertical header, and into one of three horizontal ducts to the tunnel's nozzle. Gate valves in the inlet and outlet ducts isolated and controlled flow through each tunnel. The primary measurements made in the SSTs were of pressures and flows. None of these tunnels featured a force-and-moment balance. Schlieren systems were also used extensively for flow visualization since many of the test programs involved the management of intake shocks.

HISTORY

The advent of jet aircraft and the V-2 missile during World War II prompted aeronautical engineers at the NACA and elsewhere to start thinking seriously about supersonic flight. The German V-2 had proven vehicles could survive flight at speeds greater than Mach 1, but American engineers knew very little about supersonic aerodynamics or propulsion when word of the early V-2s and Messerschmitt Me-262 jet fighters came from Europe during the war's final year. A few of the AERL engineers had seen the twin-jet Bell YP-59A Airacomet during its secret tests in the AWT, and those tests, plus the plane's disappointing in-flight performance, verified that America had much to learn about jet engines and aircraft.

While many within the NACA expressed little interest in supersonic aerodynamics, the topic did have a few champions, including Abe Silverstein, manager of the AWT at the AERL. With the AWT having entered service in February 1944, Silverstein started to think ahead, and he discussed the idea of a supersonic wind tunnel at the laboratory with NACA Director of Aeronautical Research George W. Lewis. Lewis was encouraging, but Silverstein knew a large supersonic tunnel would take several years to fund, design, and build.

In the meantime, Silverstein thought that a smaller supersonic tunnel using the AWT's air-handling equipment might be a practical venture, and he assigned DeMarquis D. Wyatt, a young but capable engineer, to design and build one. Wyatt may not have known much about wind tunnels when he began the effort in early 1945, but his mentor, Silverstein, had had years of experience at Langley before moving to Lewis. The design process seems to have been a combination of rudimentary theoretical analysis, judgment, and empiricism, and the small group finally decided to build two tunnels. One would be 18 inches square, the second circular and 20 inches in diameter, and both would be operated at around Mach 2.[32]

The limited space available between the AWT and IRT, the only location convenient to the makeup air dryer, dictated that two tunnels would have to be either vertically oriented or, if horizontally oriented, built with one over the other. Wyatt and Silverstein chose the latter option and built a four-story, L-shaped masonry building with concrete floors to enclose the test sections. The test chamber portion was rectangular in plan and included a control room on the ground floor. A narrower leg extended from its northeast corner to enclose a stairwell, plus a small office on the ground floor. Whether or not plans already existed for a third tunnel is unknown, but a January 1946 cutaway rendering shows three tunnels plus an exhaust manifold directly to the exhauster building that was not part of the initial installation.[33]

Tunnel Number 1, the 18- by 18-inch tunnel, was built on the second floor, with 20-inch-diameter Tunnel Number 2 on the third floor. Exactly when they entered service is uncertain. Operation of Tunnel Number 1 began in June 1945. A photograph dated 10 September 1945 shows Tunnel Number 1 complete, but with construction barely under way on Tunnel Number 2, which was completed in 1949. Both opened with speeds of approximately Mach 1.9, but within a year, the engineers had designed nozzles for additional speeds between Mach 1.4 and 3.2.[34]

Tunnel Number 3, the largest and fastest of the three at 24 by 24 inches, was installed on a fourth-floor addition to the building, and it entered service during fall 1949. Its specifications, including a speed range of Mach 3.0–4.5, indicate that the engineers at the renamed Lewis Flight Propulsion Laboratory (LFPL) must have learned a great deal from their initial efforts before designing this tunnel. Two years later, they replaced the original, circular test section of Tunnel Number 2 with a square one measuring 18 by 18 inches and featuring an operating speed of Mach 3.05.[35]

The first two SSTs generated considerable research interest soon after they opened. As expected at a propulsion laboratory, most of the test programs explored some aspect of engine performance at supersonic speeds. A particular area of interest was jet engine intakes, because air must be moving below Mach 1 when it encounters the first compressor blades, regardless of the airplane's speed. Thus, the inlet must act like a diffuser to slow supersonic air, and it must do this without having shock waves strike the engine. Inlets with variable throats and inlet spikes were some of the more significant designs investigated during the tunnels' early years, but a number of test programs involving airframe design were also conducted.[36]

Most SST testing was done during the day, when the exhauster system was not needed by the AWT, which operated almost exclusively at night, although the setup time between AWT test programs could also be used. The SSTs did not need the AWT's main refrigeration system, but they did utilize the York refrigeration system that served the makeup air dryer. In most cases, an SST and the IRT could run simultaneously, since the IRT used the AWT's refrigeration system, but only a little of its exhauster capacity on some runs, and none on many.

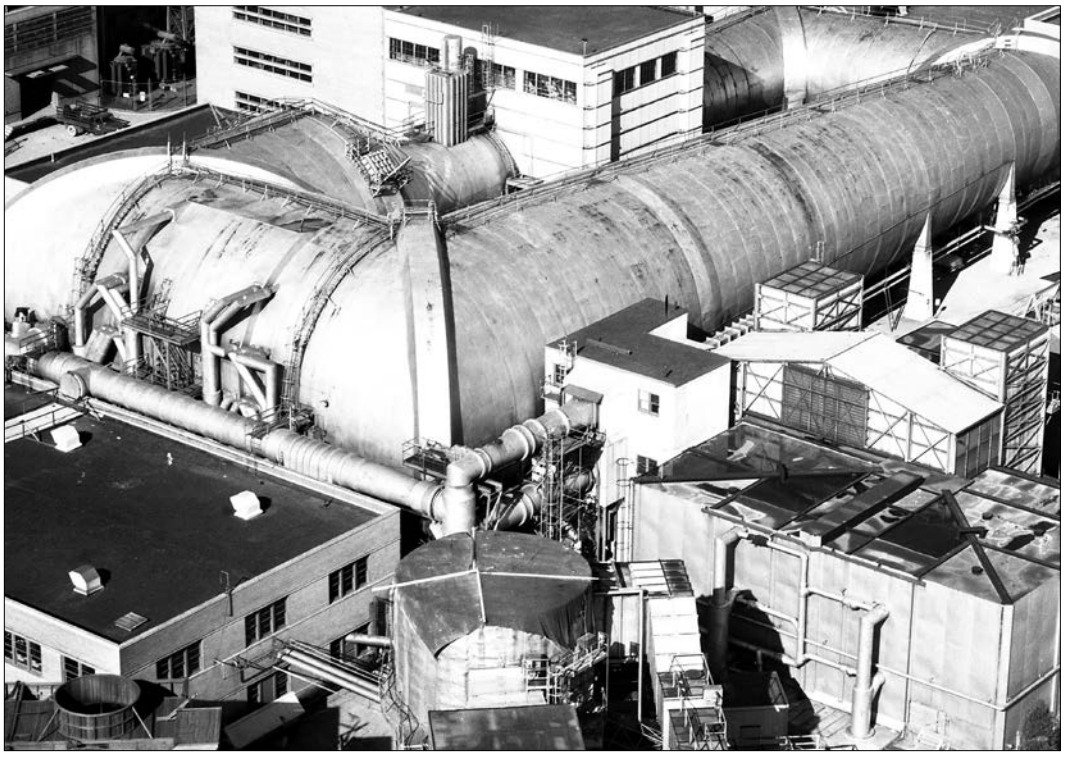
A detailed, cutaway, pictorial drawing of the facility dated 22 January 1946 shows three tunnels in a four-story building, with all three tunnels connected to a large, vertical exhaust manifold. Thus, the manifold, which had an underground pipe to the exhauster building, appears to have been installed as part of the project to add the third tunnel in 1949.[37]

The three SSTs remained in service until 1959. While the NACA published only a few test reports based on work done solely in these tunnels, it published a number of reports of work done in Lewis's larger tunnels that clearly had their antecedents in the SSTs. The three tunnels were excellent venues for preliminary testing that would have led to more focused programs in the larger, more-expensive supersonic tunnels and resulted in considerable cost savings.[38]

As at the other NACA laboratories, the creation of NASA in November 1958 brought tremendous change to the renamed Lewis Research Center. Its focus shifted heavily from jets toward advanced rocket engines, due in no small measure to Lewis's success in addressing the problems of the former. Turbine-engine work remained to be done, but it was not the kind of preliminary work best suited for the SSTs, and management decided to close them in 1959. With no need existing for the compact space, the structure remained in place, and it came to be used for storage by various facilities maintenance contractors for a number of years. The vertical exhaust manifold remained in service but sealed off from the tunnels. One tunnel connection was rerouted to what became Chamber Number 2 of the Space Power Chambers, and an exhaust was installed from the IRT's test section to allow engine flows to be simulated during icing tests of inlets.[39]

Between 1982 and 1986, various other parts of the unused tunnels were removed for reuse or scrapped. The decision to rebuild the IRT in 1986 finally sealed the fate of the remaining portions of the SST complex, including the exhaust manifold. The space was needed for an IRT auxiliary building, and the final remnants of the SSTs were demolished in 1987. No portion of any SST is known to survive.

This control room on the building's ground floor served all three of the Small Supersonic Tunnels. (Photo credit: NASA GRC-1945-C-13689)



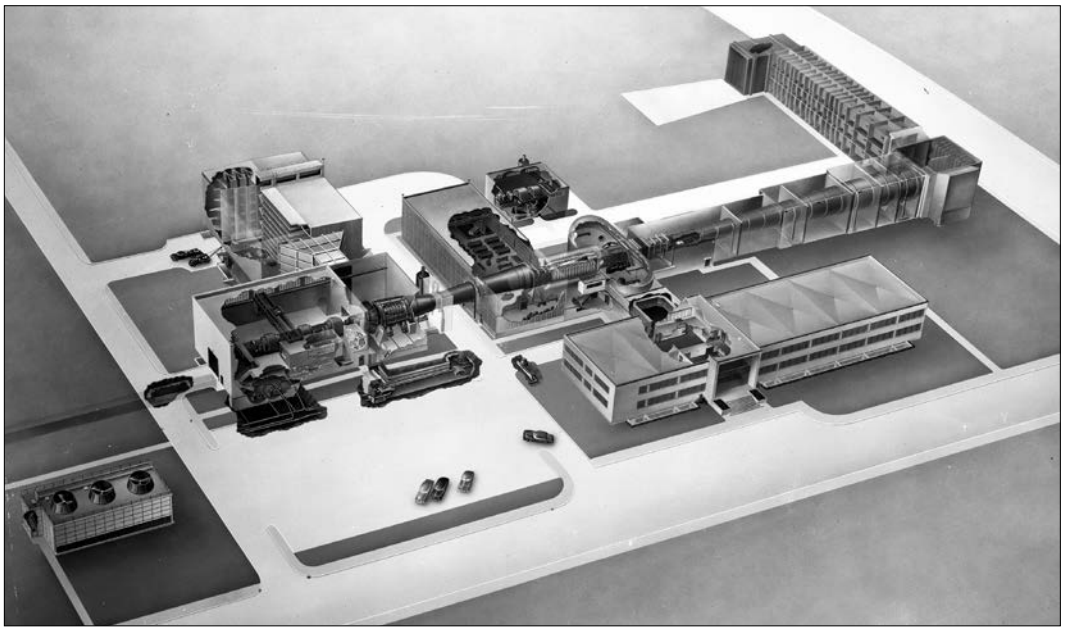
The small space available for the Small Supersonic Tunnels between the Altitude Wind Tunnel and the Icing Research Tunnel is clearly evident in this April 1955 view, which also shows the inlet duct from the makeup air dryer at lower right. Note the gate valve in the top tunnel's inlet duct, the top of the exhaust manifold at top center, and the makeup air duct to the AWT at the left. (Photo credit: NASA GRC-1955-C-38653)

The first two Small Supersonic Tunnels had their exhaust ducts connected to the Altitude Wind Tunnel (top). The vertical exhaust manifold (bottom) had a direct underground pipe to the exhauster building, and it permitted additional connections from the third SST, the Icing Research Tunnel's test section, and Space Power Chamber Number 2. (Photo credit: NASA GRC-1945-C-10764 and NASA GRC-1947-C-18978)

Circular Tunnel Number 2, shown here in 1945, was replaced with a faster 18- by 18-inch tunnel in 1951. (Photo credit: NASA GRC-1945-C-13686)

A technician is preparing for a test run in 18- by 18-Inch Tunnel Number 1 in 1952. (Photo credit: NASA GRC-1952-C-30700)

8- BY 6-FOOT SUPERSONIC WIND TUNNEL
9- BY 15-FOOT LOW-SPEED WIND TUNNEL



This 1953 cutaway rendering shows the 8- by 6-Foot Supersonic Wind Tunnel after the muffler addition in 1950. The proposed return leg at the top was added in 1957 to complete the closed circuit. Not shown are the doors in the return leg that allow open-circuit operation. (Image credit: NASA GRC-1953-C-31663)

SIGNIFICANCE

The 8- by 6-Foot Supersonic Wind Tunnel (8- by 6-Foot SWT) was the first large supersonic wind tunnel at the Lewis Flight Propulsion Laboratory, and it was the first tunnel designed specifically to test operating jet engines at speeds above Mach 1. When opened, the 8- by 6-Foot SWT was the world's largest supersonic wind tunnel. Although it was originally built as an open-circuit tunnel, subsequent modifications converted it into one able to operate in either open- or closed-circuit mode and added transonic capability. This tunnel is now NASA's primary facility for transonic engine testing.

A later modification involved the installation of the 9- by 15-Foot Low-Speed Wind Tunnel (9- by 15-Foot LSWT), a second, low-speed test section in the return leg. It remains one of NASA's premier facilities for acoustic studies and large-scale-model subsonic testing.

DESCRIPTION

The 8- by 6-Foot SWT/9- by 15-Foot LSWT is a dual-test-section, closed-circuit wind tunnel that can also operate in an open-circuit mode. Although operated as separate wind tunnels, the two test sections utilize a common drive and circuit. The facility has undergone several major renovations since originally opening as the open-circuit 8- by

6-Foot SWT, including additions that closed the circuit and the installation of the 9- by 15-Foot LSWT.

The 8- by 6-Foot SWT/9- by 15-Foot LSWT is a modern wind tunnel fabricated largely of steel, but it differs in several ways from its contemporaries, and certain details preferred by Lewis engineers are rarely, if ever, found in tunnels at other NASA centers. The 8- by 6-Foot SWT/9- by 15-Foot LSWT is a mix of circular and rectangular cross sections. Unlike most modern tunnels, the 8- by 6-Foot SWT was not fitted with turning vanes until acoustic vanes were added to Turns 2 and 3 in 2018. This omission was not due to any design philosophy, but rather to the incremental evolution of the tunnel. The original 8- by 6-Foot SWT was a linear tunnel, with all but its air dryer on the same centerline. The large air dryer was placed at 90 degrees to this centerline to avoid having to have bypass ducts around the motor room, as well as to better fit the facility into the available space. The right-angle turn from the dryer to the compressor was designed as a plenum with the compressor inside it, arranged so its discharge duct penetrated one wall. Its flared inlet opened to the plenum, guarded by a toroid-like screen with a triangular cross section (an unusual design repeated in Lewis's Unitary Plan Wind Tunnel, but rarely elsewhere). Installation of the large acoustic muffler downstream of the 8- by 6-Foot SWT test section required a second right-angle turn between the diffuser and the muffler, but no vanes were installed. Later, when the return leg was added, the need for doors to admit outside air to the dryer during open-circuit operation was originally thought to preclude the installation of turning vanes in the last corner. In deference to the harsh Cleveland winters, much of the tunnel is inside concrete structures. Only two short runs and the semi-cylindrical vacuum chamber that houses the test chamber are externally visible.[40]

The tunnel's air dryer, believed to be the largest built up to 1947, originally contained 1,250 tons of activated alumina desiccant spread 2 feet thick on multiple horizontal beds with a total surface area of 23,520 square feet. Today, the dryer contains alternating beds of alumina and silica.[41] It was designed to take in 1,800,000 cubic feet of air per minute at 73°F dry bulb and reduce its dew point from 67 to –20°F for 56 minutes. These numbers vary for different operating conditions. The desiccant is reactivated by heating it for 4 hours, after which it is allowed to cool for between 2 and 4 hours before the next run.

Airflow is generated by a seven-stage axial compressor that can generate test speeds between Mach 0.25 and 2.0 in the 8- by 6-Foot SWT, or Mach 0.05–0.22 in the 9- by 15-Foot LSWT. Three 29,000-horsepower, wound-rotor induction motors turn the 18-foot-diameter compressor at speeds of up to 880 revolutions per minute. This speed variation, in conjunction with adjustments to the 8- by 6-Foot SWT's flexible nozzle, allows the tunnel's wide range of test speeds. Liquid rheostats furnish motor speed control. In 1995, engineers modified the drive system to allow the operation of a single motor, a change that reduced power consumption and provided improved operation at lower speeds.[42]

The 8- by 6-Foot SWT utilizes a flexible-wall nozzle to produce and control supersonic flow in the test section. A circular duct runs from the compressor outlet, over a driveway, and through the model shop building, where it transitions to rectangular and joins the nozzle. The floor and ceiling are fixed, and each of the two side walls is contoured by 14 hydraulically actuated jackscrews. All four walls are 1-inch-thick polished stainless steel, and the nozzle measures 35 feet, 6 inches long.

The 8-foot-high by 6-foot-wide test section is enclosed in a semi-cylindrical steel housing that Lewis/Glenn people call the balance chamber. This balance chamber has quarter-spherical ends and external strengthening ribs. Since this is an atmospheric tunnel, this construction was used to efficiently resist the partial vacuum created by the high-speed air in the test section. The test section was fabricated from polished stainless steel, and it stretches 23 feet, 6 inches in length. Until 1956, its walls were solid, although the side walls had two eccentrically mounted, optically flat windows for schlieren photography. That year, all four walls of the trailing 14 feet, 5 inches of the test section were drilled with over 4,500 holes to provide transonic test capability. The 1-inch holes, drilled at a 30-degree angle to the flow, were arranged in chevron patterns.[43] Blanking plugs allow the porosity to be varied between approximately 3 and 6 percent, and the second pair of schlieren windows can be replaced with perforated panels. The first 9 feet, 1 inch of the test section remains solid-walled and reserved for supersonic tests. Floor, ceiling, and side wall mounts for engines and models are available, plus a jet-exit strut for exhaust nozzle testing. Compressed air, water, fuel, and a hydraulic system support model operation.

Leaving this test section, the air flows down a 226-foot-long diffuser that transitions to circular and expands to a diameter of 26 feet. Originally, this diffuser ended at a cubical concrete structure that had baffles to split and turn the air 90 degrees where it exhausted to the atmosphere through two large grills. Excessive noise during the tunnel's operation resulted in a modification to the diffuser and the addition of a muffler extension built at a right angle to the diffuser. A concrete shell around the diffuser contains resonator chambers that attenuate sound in the 5– to 11– Hertz range. The steel diffuser is slotted to communicate with the chambers. In 1950, both grills in the original discharge chamber were removed. One grill was blanked off, and an acoustic muffler, which created a 90-degree turn, was added to the other. The new 152-foot-long, concrete structure is divided into two sections, each having six parallel passages measuring approximately 10 feet square. The first section attenuates frequencies between 12 and 20 Hertz, while the second is designed to reduce 20– to 200–Hertz sound. The diffuser and first part of the muffler work as Helmholtz resonators tuned to different frequencies; the second muffler section is lined with acoustically treated, soft-walled panels.[44] The muffler measures 34 feet wide by 41 feet high, and its exit is another 90-degree turn.

The final leg to complete the circuit, installed during 1956–57, was built of concrete, and it connects the muffler exit with the air dryer's inlet. Doors at each end of this leg

allow the 8- by 6-Foot SWT to operate in an open-circuit "propulsion cycle" mode when opened, or in a closed-circuit "aerodynamic cycle" mode when closed. Originally, when in open-circuit cycle, another door also closed off the return leg. When the second test section was installed, this door was replaced with doors on both ends of the new test section. To keep the air temperature below 85°F during aerodynamic cycle runs, a finned-tube cooler after the first rolling doors transfers excess heat to water that circulates to a cooling tower.

In 1968 and 1969, a second test section, known as the 9- by 15-Foot LSWT, was installed in the return leg. It originally consisted of an inlet contraction, test section, diffuser, and isolation doors at each end. These doors are closed whenever the 8- by 6-Foot SWT is operating in its open-circuit cycle, and they allow model setup work to continue uninterrupted in the 9- by 15-Foot LSWT. The 9- by 15-Foot LSWT's original test section measured 28 feet, 7 inches in length, and each side wall had four 4-inch-wide slots to reduce wall interference effects on the model. The test section has undergone many upgrades since 1968, including its lengthening by 5 feet at the downstream end in 2018. The walls could be fitted with acoustic panels, with slots that communicated to cells containing a low-density aramid-fiber filling. These slots no longer exist. A set of four screens and a honeycomb flow straightener upstream of the contraction smooth the airflow.[45]

As aircraft have grown quieter at about 1 decibel per year, the background noise levels of the 9- by 15-Foot LSWT have remained the same. Without a reduction in tunnel noise, measurement of the engine noise signature becomes difficult, if not impossible. In 2019, five modifications were completed to the tunnel circuit to reduce noise. Acoustic turning vanes were added to Corner 2 to efficiently turn the airflow and absorb noise. Acoustic serpentine baffles were added to block and absorb noise downstream of the cooler. In addition, the test section's overall length was increased to 32 feet, 8 inches, and the acoustic treatment was upgraded to reduce background noise and noise reflections from the model. The new flow surfaces consist of a micronic wire cloth diffusion bonded to a high percent open area perforated plate, and the slots were removed. This construction provides a smooth and quiet boundary to contain the flow while allowing sound waves to enter acoustic boxes that do not reflect the sound back into the test section. Also, the diffuser geometry was changed to efficiently slow airflow, and noise-reducing acoustic treatment was added. Finally, acoustic turning vanes were added to Corner 3 to efficiently turn the airflow toward the compressor and absorb noise. The five modifications reduced the 9- by 15-Foot LSWT's background noise by about 10 decibels overall. These acoustic improvements allowed this unique facility to continue to support research that reduces noises and improves fuel efficiency in engines for years to come. [46]

The 9- by 15-Foot LSWT operates only in a partially closed-circuit mode. Initially, the dual rolling doors normally used for selecting the open or closed-circuit cycle in the 8- by 6-Foot SWT were adjusted to control the flow through the 9- by 15-Foot LSWT,

since partially opening them reduced the volume of air passing through the test section. This, in conjunction with the compressor speed, permits the control of the tunnel.[47]

Models in the 9- by 15-Foot LSWT are generally mounted on its offset turntable, which allows for yaw angle actuation of a model. Since models testing for acoustics in the tunnel are typically mounted "sideways," this equates to actuation of model pitch in the yaw plane. In the past, models could be mounted on a Model Integrated Support System (MISS), which allowed movement in pitch, yaw, roll, and height above the floor and facilitated the evaluation of V/STOL aircraft and the flow fields around them. Models can be furnished with compressed air, heated air to simulate combustion air, gaseous nitrogen, and a hydraulic system for controls. Various flow visualization and measurement systems can be installed. When needed, signals from strain gages in the model can be processed and recorded as force and moment data from a six-component balance.

The facility's control room is located between the two-story office building on the tunnel's north side and the 8- by 6-Foot SWT balance chamber. Its equipment has been upgraded several times since 1968. It now includes modern model control systems along with higher-frequency data acquisition that can be coupled for a more automated operation pending model details, test objectives, and tunnel operation.[48]

HISTORY

When jet aircraft and V-2 missiles appeared during World War II, aeronautical engineers began thinking seriously about supersonic flight. The German V-2 had proven vehicles could survive flight at speeds greater than Mach 1, but American engineers knew very little about supersonic aerodynamics or propulsion when the V-2s began attacking London in 1944. Early that year, the twin-jet Bell YP-59A Airacomet underwent secret testing in the AWT, and those tests, plus the plane's disappointing in-flight performance, demonstrated that America needed to take long and rapid strides simply to catch up with European technology, much less explore the supersonic flight regime.

Many within the NACA expressed little interest in supersonic aerodynamics, but a few, including Abe Silverstein, head of the AWT at Lewis, did. With the AWT having entered service testing the Bell YP-59A Airacomet in February 1944, Silverstein started to think ahead, and he discussed the idea of a large supersonic wind tunnel at the laboratory with NACA Director of Aeronautical Research George W. Lewis. Lewis was encouraging and told Silverstein to submit a proposal for one.

Silverstein was pleased, but he knew a large supersonic tunnel would take several years to design, fund, and build, so while he pursued the large supersonic tunnel, he assigned one of his young engineers to design and build something smaller that could utilize the AWT's services. Such a tunnel could be placed in service quickly and cheaply, and it would serve as a training ground for his engineers while the larger tunnel was being built. The result was initially a pair—later three—tunnels collectively known as the Small Supersonic Tunnels, or simply the Stack Tunnels, the first of which opened in mid-1945.[49]

During this period, Silverstein prepared and submitted his proposal for a supersonic tunnel capable of testing turbojet, ramjet, and turboprop engines in operation. After evaluating the pros and cons of several test section sizes, he settled on 8 by 6 feet as a reasonable compromise of costs and capabilities. Unlike the closed-circuit AWT, which required enormous exhausters, Silverstein and engineers working with him, including DeMarquis D. Wyatt and John Disher, chose to give the new tunnel an open circuit. This would eliminate any possibility of an engine under test reingesting its contaminated exhaust gases. Even with this basic design decision made, they analyzed several conceptual designs before selecting the one actually built. That design included a massive air dryer, the largest built to that time, and a linear tunnel that used a forced-draft axial compressor to blow air through the supersonic nozzle, test section, and diffuser, where the air exited to the atmosphere. The desired speed of Mach 2 required an 87,000-horsepower drive, accomplished with three 29,000-horsepower electric motors. They estimated that the tunnel would cost around $6 million to build.[50]

The proposal meshed well with the NACA's overall plans for the agency and the Lewis Laboratory. It soon received the necessary funding from Congress, and construction began in 1946. Lewis unveiled the nearly completed facility on 28 September 1948. Several days of test and calibration runs began on 3 April 1949, and the 8- by 6-Foot SWT commenced actual test work immediately thereafter.[51]

While the tunnel functioned well during the first several months of testing nonoperational models, the first attempt to fire a ramjet engine at supersonic speeds revealed one major problem—noise. Since the tunnel and jet exhaust was directed to the atmosphere, test runs rattled windows well beyond the laboratory's boundaries, and nearby residents quickly made their displeasure known. Several sources referred to the incident as "an 87,000-horsepower bugle aimed at the heart of Cleveland." Engineers from the Bolt and Baranek Company, a well-known acoustical consulting firm, began studying ways to reduce the noise level, and they devised a three-stage muffler, with each stage to attenuate a portion of the total frequency range of the noise, using the principle of a Helmholtz resonator. The first section was built around the existing diffuser, while the second and third stages involved the construction of a new, 152-foot section at a right angle to the original tunnel. Completed in 1950, this acoustical muffler reduced the tunnel's noise to tolerable levels.[52]

Despite competitive concerns by the various engine manufacturers that limited the number of outside test programs in the 8- by 6-Foot SWT during the 1950s to something less than anticipated, the tunnel proved to be a useful tool for NACA researchers studying ramjets and their possible applications. Other research programs examined topics such as engine inlet and exhaust nozzle airflows. When NASA was formed in 1958, the 8- by 6-Foot SWT staff was well positioned to conduct a wide variety of test programs involving rocket nozzle efficiency, directional control, and the dynamic stability of missile and spacecraft designs.[53]

With the volume of aerodynamic test programs growing during the 1950s, Lewis management decided to convert the open circuit into one capable of operating in either a closed- or open-circuit mode and to modify the test section to permit transonic testing. Lewis received approximately $2 million to do this work, which it did during 1956–57. The closed-circuit "aerodynamic cycle" improved temperature stability in the tunnel and extended the air dryer's desiccation time to several hours between alumina reactivations, while the open-circuit "propulsion cycle" retained its capabilities, but over a wider speed range. Almost all of the boosters and spacecraft used in the Mercury, Gemini, and Apollo programs were at some point tested in the 8- by 6-Foot SWT.[54]

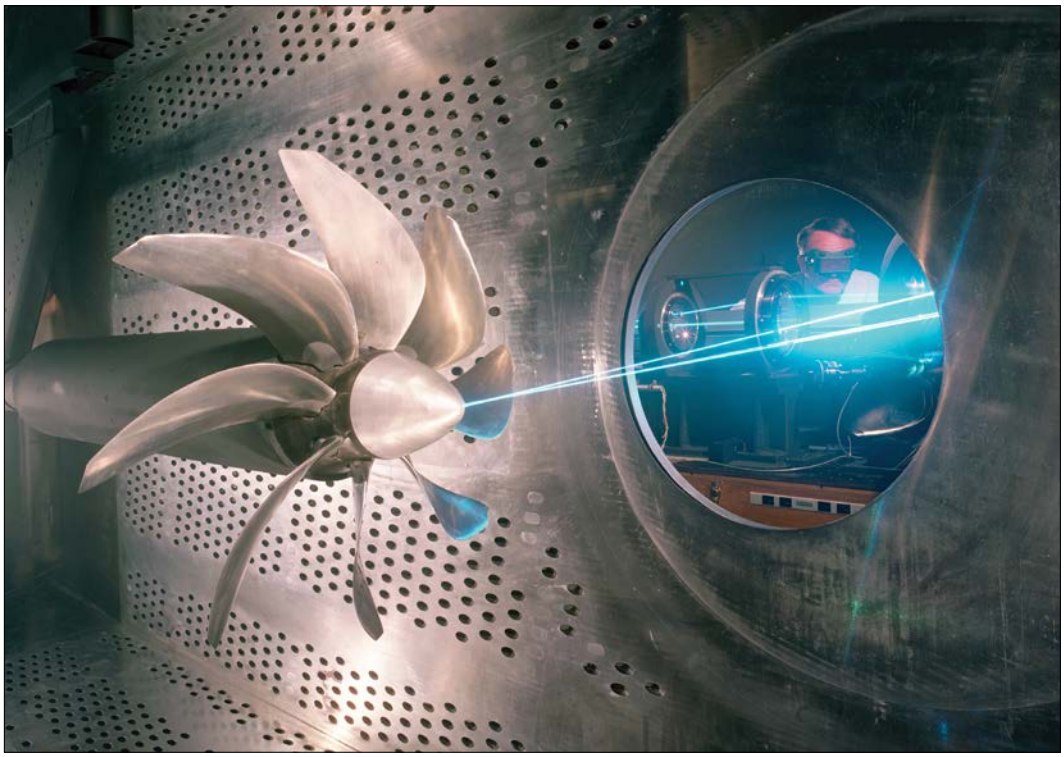
During the 1960s, interest in supersonic research peaked, spurred by the program to build an American supersonic transport (SST) that would best the Anglo-French Concorde, but it waned after the program was terminated in 1971. By then, jet propulsion had become the dominant form of power in all but the slowest and lightest aircraft, and considerable research was needed in everything from turboprops to V/STOL concepts—all subsonic applications. V/STOL craft generated particular interest since such a plane could take off and land much like a helicopter, yet cruise much faster like an airplane. Many V/STOL concepts used some form of thrust vectoring, where jet exhaust and/or fan thrust was directed downward to provide lift at zero forward speed, but then gradually redirected toward the rear to increase the craft's speed and let its wings generate lift as the thrust generated speed. Some of these designs used ducted-fan engines on rotating pods, while others employed movable elbows to change the thrust angle. All of these concepts exhibited difficulties with marginal power, reliability, and controllability, plus a couple of unique problems. Near the ground, the engine could reingest its own exhaust gases instead of clean air and experience an abrupt loss of power. And during transition from hovering to horizontal flight, crossflow air currents seriously challenged the ability of control thrusters to maintain stable flight.

A small group of engineers at Lewis led by Joseph A. Yuska, James H. Diedrich, and Nestor Clough realized the need, and their studies indicated that a second test section could be installed in the 8- by 6-Foot SWT's return leg that would have both the speed range and size necessary for V/STOL research. By utilizing the 8- by 6-Foot SWT's drive and structure, they estimated that it could be built for less than $700,000. Their proposal was accepted, and the team began detailed design work. Two areas of concern were the designs for the inlet contraction and the test section wall slots needed to reduce wall interference effects. In both cases, they were able to draw upon earlier work at Langley and Ames to calculate the parameters needed, but their design was specific to their situation.[55]

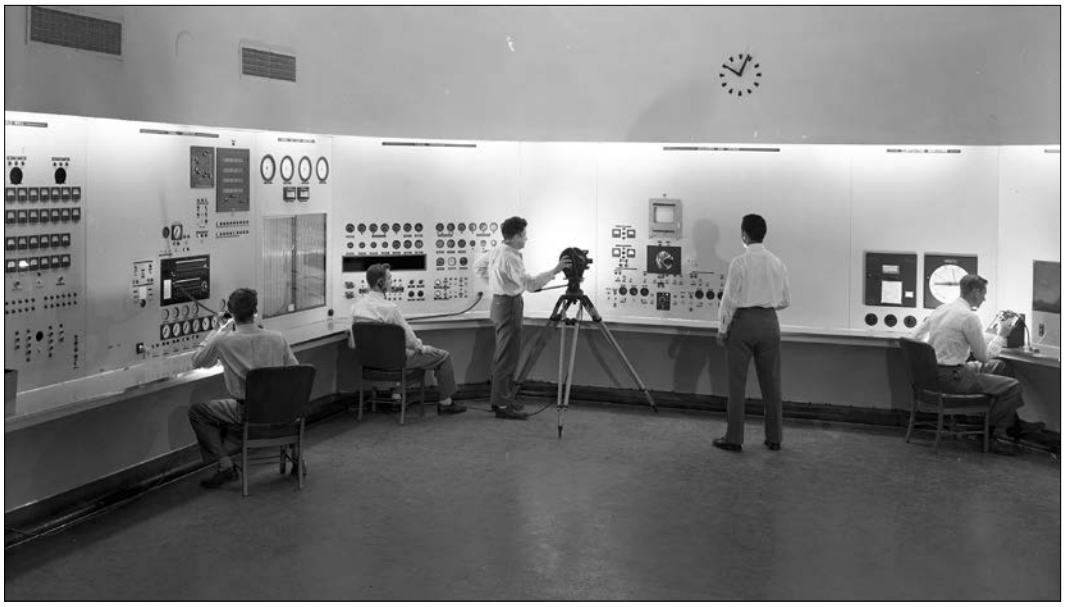
Operational in 1968, the 9- by 15-Foot LSWT, as the new facility was named, soon demonstrated its suitability for V/STOL research, but it also became an excellent venue for a variety of tests of large-scale hardware at speeds of up to approximately 175 miles per hour. In addition to V/STOL investigations, the tunnel's crossflow capabilities allowed more-advanced research into the performance of engine inlets, exhaust nozzles,

and propellers in complex airflow situations. A multi-axis model actuation system and new flow techniques enabled detailed studies of the complex airflow patterns around both conventional and V/STOL engines. The 9- by 15-Foot LSWT has become one of NASA's most cost-effective facilities for a host of noise-reduction studies. The facility underwent acoustic upgrades in the mid-1970s and the mid-1980s; the latter included new acoustic panels that were a major improvement. A mid-1990s modification to the facility's drive to allow single motor operation improved the tunnel's performance and economy during low-speed operation. In the late-2010s, there was a major acoustic upgrade (described earlier) to the 9- by 15-Foot LSWT and the entire return leg of the 8- by 6-Foot SWT.[56]

Both test sections have seen tests in support of significant aeronautical achievements, including the center's advanced turboprop (ATP) work that earned it the Collier Trophy for 1987. In 2007, the 8- by 6-Foot SWT was determined to be eligible for listing on the National Register of Historic Places because of its contribution to the Space Shuttle Program. The 8- by 6-Foot SWT/9- by 15-Foot LSWT complex's bookings allowed it to survive NASA's "full cost accounting" program that closed many tunnels during the late 1990s, and at 75 years of age, it remains in service as one of NASA most flexible facilities.[57]



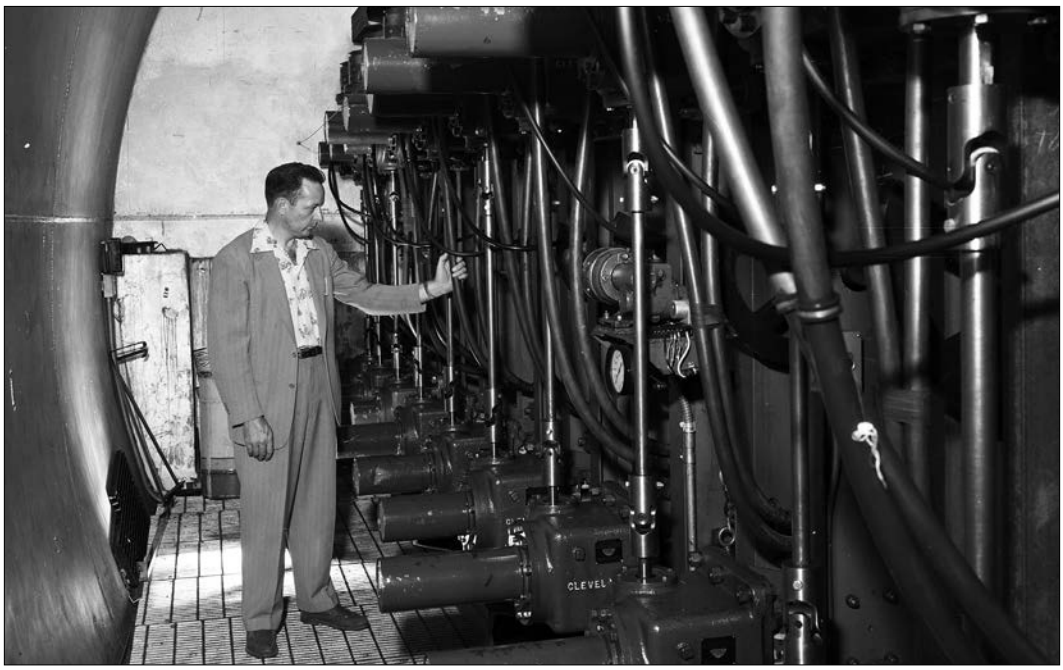
Engineers at Lewis developed a series of advanced propellers with complex blade shapes during the 1980s. Here lasers make precise measurements of blade deflections during a test run in the 8- by 6-Foot Supersonic Wind Tunnel in 1979. (Photo credit: NASA GRC-1979-C-03424)



The 8- by 6-Foot Supersonic Wind Tunnel was originally operated from this control room, seen here in 1949. It has since been fully renovated with computerized controls. (Photo credit: NASA GRC-1949-C-24643)

The stator case of the 8- by 6-Foot Supersonic Wind Tunnel's seven-row compressor, seen here in 1949, can be opened for inspection and maintenance. Three electric motors totaling 87,000 horsepower turn it. Note the toroid-like screen at the compressor's inlet. (Photo credit: NASA GRC-1949-C-23277)

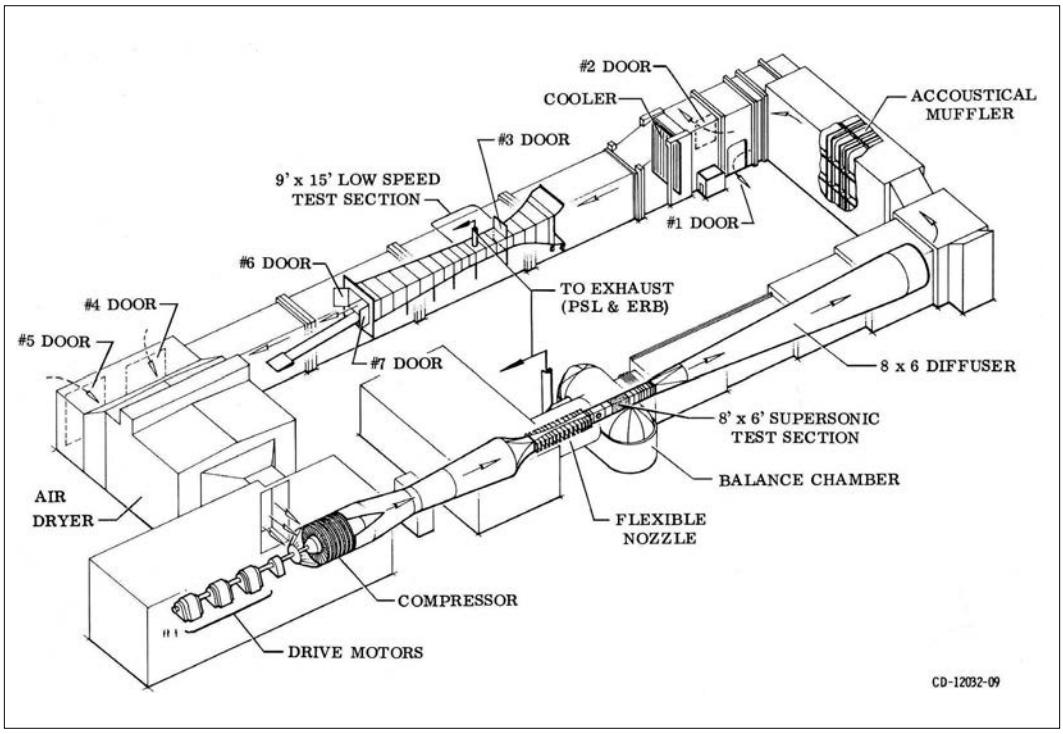
This 1950 interior view of the 8- by 6-Foot Supersonic Wind Tunnel's diffuser exit (left) also shows the entrance to the muffler section addition (right). (Photo credit: NASA GRC-1950-C-26414)



An engineer inspects the jack system in 1955 used to adjust the 8- by 6-Foot Supersonic Wind Tunnel's flexible-wall nozzle and change the tunnel's speed. (Photo credit: NASA GRC-1955-C-38859)

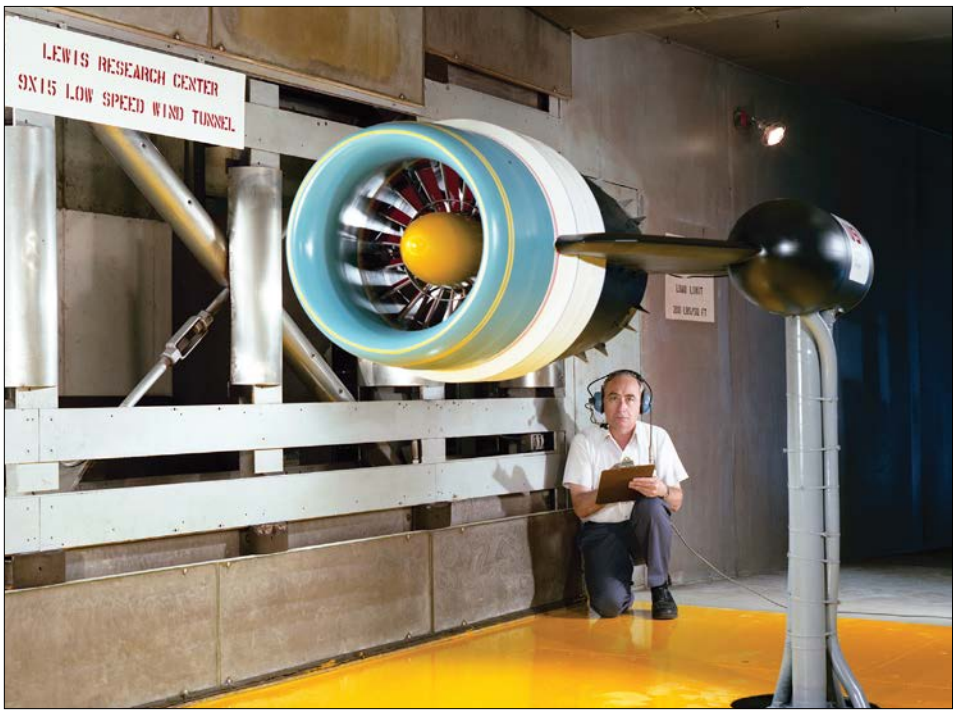
After 1957, the 8- by 6-Foot Supersonic Wind Tunnel's test section featured the perforated walls shown here with technicians preparing a ramjet inlet for testing. They allowed the tunnel to operate at transonic speeds. Note the eccentrically mounted observation window in the side wall. (Photo credit: NASA GRC-1957-C-45653)

The current external appearance of the 8- by 6-Foot Supersonic Wind Tunnel and 9- by 15-Foot Low-Speed Wind Tunnel complex seen here in 1968. (Photo credit: NASA GRC-1968-C-01956)



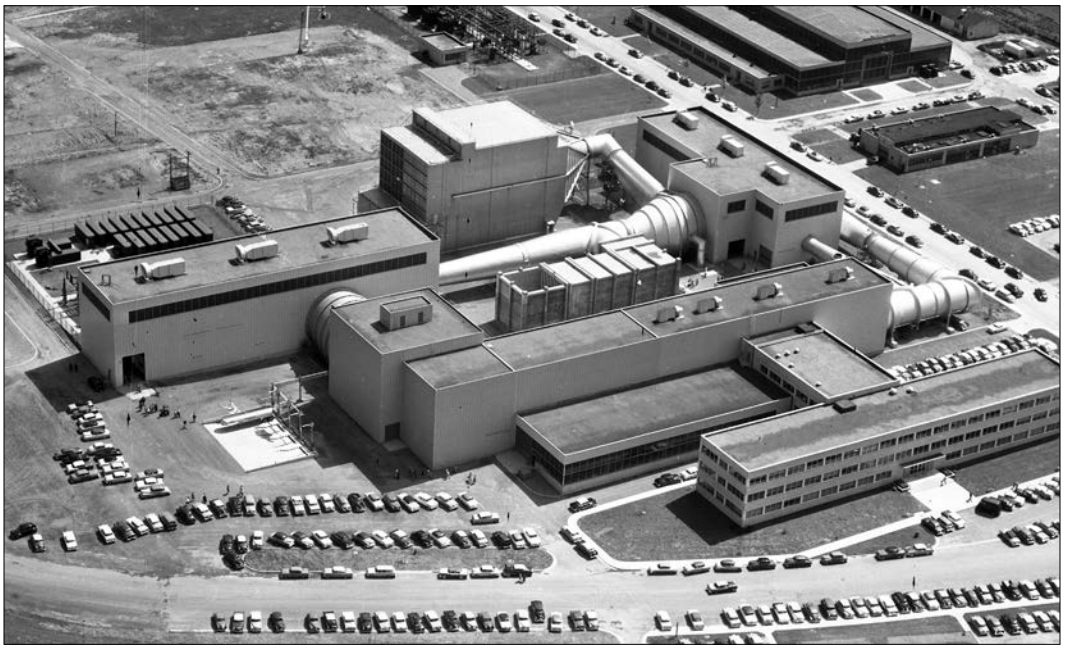
This drawing shows the facility's current arrangement with two test sections. The seven numbered doors open and close to change the 8- by 6-Foot Supersonic Wind Tunnel from closed to open mode and isolate the 9- by 15-Foot Low-Speed Wind Tunnel when the 8- by 6-Foot SWT is running in open mode. The three small figures of people standing next to the drive motors provide a sense of the tunnel's size. (Image credit: NASA CD-12032-09)

The 8- by 6-Foot Supersonic Wind Tunnel had the most modern data acquisition and data-processing equipment available when it opened, and its capabilities have been upgraded numerous times. Some of the early equipment is shown here, including (top left) manometer panels and a telereader (1952), (top right) an NACA-developed automatic data recorder (1952), (bottom left) an IBM 604 electronic calculator (1952), and (bottom right) an EIA Pace 16-31R analog computer (1959). Note the circuit plugboards that had to be wired with jumpers to "program" the machines. Fully automated data acquisition and digital computer equipment came later. (Photo credits: NASA GRC-1952-C-29211, NASA GRC-1952-C-31564, NASA GRC-1952-C-30194, NASA GRC-1952-C-31565)



The 9- by 15-Foot Low-Speed Wind Tunnel has proven to be a versatile addition to the facility's capabilities. At the top, a turbofan engine is undergoing acoustical tests in 1980 aimed at reducing noise levels. The large model and flow field in the lower view is being examined with a laser sheet in 1993 to investigate ways to minimize the re-entrainment of exhaust gases during vertical landings. (Photo credits: NASA GRC-1980-C-04517 and NASA GRC-1993-C-07355)

ABE SILVERSTEIN 10- BY 10-FOOT SUPERSONIC WIND TUNNEL



This 1956 aerial view shows the size and extent of the 10- by 10-Foot Supersonic Wind Tunnel complex, except for its cooling tower, which is out of sight below the photograph. The tallest structure at top center is the air dryer. The test section is in the central building with four roof ventilators, and the two structures with three roof ventilators each house the drive motors and compressors. (Photo credit: NASA GRC-1956-C-42303)

SIGNIFICANCE

The 10- by 10-Foot Supersonic Wind Tunnel (10- by 10-Foot SWT), which was rededicated as the Abe Silverstein Supersonic Wind Tunnel in 1994, is one of a group of large, high-performance wind tunnels built under a joint, or "unitary," appropriation by Congress to provide supersonic wind tunnels for both military and civilian research and development. A new supersonic tunnel was built at each NACA laboratory and at a new Air Force development center.

Lewis's 10- by 10-Foot SWT was originally intended primarily for supersonic aircraft engine research, and it has the largest supersonic test section of the NACA Unitary Plan tunnels. America's most powerful wind tunnel, it features two compressors with two sets of drive motors and the ability to operate in both open- and closed-circuit modes. The 10- by 10-Foot SWT has tested most American jet engines, missiles, supersonic aircraft, and spacecraft built since 1956.

Abe Silverstein (1908–2001) had a distinguished, 40-year career as an engineer and manager for the NACA and NASA, including service as Director of Lewis Research Center from 1961 to 1969. On 15 October 1994, NASA renamed the 10- by 10-Foot SWT in his honor.

DESCRIPTION

The 10- by 10-Foot SWT, which was known as "LUPA" (Lewis Unitary Plan Act) Tunnel during its design and construction phases, is a large, complex supersonic wind tunnel that features a single test section, but multiple combinations of open- and closed-circuit operation using one or two sets of compressors and drive motors. It has the capability of testing a wide variety of airframe and component designs, as well as operating jet engines at speeds between Mach 2.0 and 3.5, in addition to a low-speed range from zero to Mach 0.36, and simulated altitudes of up to 150,000 feet. In addition to the tunnel itself, the 10- by 10-Foot SWT complex includes buildings enclosing the nozzle, test section, diffuser, and cooler; two motor buildings; an air dryer, sound muffler, and cooling tower; and a three-story office and shop building. Approximately one-half of the 10- by 10-Foot SWT's circuit is enclosed, and the complex occupies an area approximately 600 by 600 feet, plus space for a cooling tower south of Walcott Road.[58]

The core of the 10- by 10-Foot SWT is a closed circuit fitted with an adjustable nozzle, single test section, and two axial compressors, but there is a bypass circuit around the second compressor. The tunnel has a circular cross section, except for the nozzle, test section, and second throat, and three of the 90-degree mitered corners are fitted with turning vanes. The shell is primarily 1-inch-thick steel plate, but high-stress portions are as much as 1.5 inches thick, with all of it fabricated and erected by the Pittsburgh–Des Moines Steel Company. A large air dryer and an exhaust silencer are connected to the tunnel's return leg in an arrangement that allows the shifting of one door in the circuit to change the tunnel from closed- to open-mode operation. Two coolers, one ahead of each compressor, remove the heat of compression produced by those compressors to maintain stable testing conditions.

The tunnel's 10- by 10-foot test section is 40 feet in length, and 33 feet, 4 inches of its floor is on an elevator that descends 16 feet to the level of the model-preparation area. The elevator is raised and lowered by four jackscrews turned by a common drive. The inner walls of the nozzle and test section are 1.375-inch stainless steel with a polished finish. Each side wall includes a personnel access door and two 5-foot-diameter ports for observation windows. Optically clear, eccentrically mounted windows with diameters of either 18 or 33 inches can be fitted as desired for schlieren photography or other observations. Models can be mounted on a sting, or on struts from the floor or ceiling, and angle of attack can be adjusted ±20 degrees upwards from horizontal or approximately –5 to +15 downwards. An adapter that enables sting-mounted models designed for the 8- by 6-Foot SWT to be tested in the 10- by 10-Foot SWT without modification is available.

Air speed in the test section is controlled by a combination of compressor speed and the contour of the flexible-wall nozzle ahead of the test section.[59] The nozzle's ceiling and floor are fixed in place, but each of the 78-foot, 3.625-inch-long walls are positioned and contoured to preset shapes by a system of hydraulically powered jackscrews. There are 27 locations on each side of the nozzle, each consisting of two jackscrews. This system is

based on, but more extensive than, the one installed in the 8- by 6-Foot SWT. Sufficient adjustment is available to vary the throat from 0.93 to 5.92 feet, which corresponds to a speed range of Mach 4.0–2.0. While the tunnel usually runs at Mach 3.5 or below, Mach 4.0 can be achieved by overloading the drive motors for a limited time.

The 10- by 10-Foot SWT also incorporates a variable second throat downstream from the test section to minimize power consumption by reducing the Mach number through a decelerating shock. It consists of two hinged panels moved by motor-driven jackscrews. The test section, nozzle, and second throat were fabricated and erected by the American Bridge Company.

The 10- by 10-Foot SWT uniquely uses two axial-flow compressors built by the S. Morgan Smith Company to move its air. Compressor Number 1 is adequate alone for test speeds of up to Mach 2.5, and Compressor Number 2 is added for higher-speed testing. Compressor Number 2 has a bypass duct that is used when the compressor is not running, but this duct is closed by a butterfly valve when the second compressor is employed. Compressor Number 1 was originally driven by four General Electric 37,500-horsepower wound-rotor induction motors, and Number 2 employed three similar motors rated at 33,334 horsepower. All seven motors were rewound in 1990, and the new insulating materials allowed heavier wire to be used, increasing each motor's horsepower to 41,250 (290,250 total horsepower). Using liquid-rheostat controls, each motor-compressor has a speed range of 450–875 revolutions per minute. Dynamic braking is employed for stopping, and a turning gear is fitted to slowly rotate the motors and compressors three times per week (originally it they were continuously rotated) prior to operation whenever the system has been idle for a day or longer.[60] This relieves any shaft sag that may have occurred that could otherwise cause excessive vibration and damage upon start-up.

Since these compressors have compression ratios of 2.8 (Number 1) and 2.4 (Number 2), compression heating of the air would rapidly raise the air temperature to excessive levels. Additional heat is introduced whenever engines are run in the tunnel, and it would drastically reduce the efficiency of Compressor Number 1 if not removed. To maintain a temperature of approximately 120°F during tests, a finned-coil heat exchanger is located ahead of each compressor. Water circulating through the coils is pumped to a 10-cell cooling tower located south of the complex that can exchange 900 million British thermal units per hour to the atmosphere.

Makeup air needed during closed-circuit, "aerodynamic cycle" operation, and all air during open-circuit, "propulsion cycle" tests, enters the tunnel through a large desiccant air dryer located outside the tunnel's circuit and connected to it at the second cooler. Measuring 117 by 84 feet in plan and 82 feet in height, it contains 1,890 tons of activated alumina arranged in six horizontal beds with a total surface area of 25,200 square feet. It was designed to take in over 1.4 million cubic feet of air per minute at 85°F (dry bulb) and reduce its dew point from 73 to –40°F for 2 hours. These numbers vary for different operating conditions, and the dryer can function for as long as 10 hours

during atmospheric cycle testing. The desiccant is reactivated by heating it for 4 hours with natural gas burners, after which it is cooled by circulating water for 4 hours before the next run. Airflow through the dryer is controlled by a set of valves in the duct connecting the dryer to the tunnel. When necessary, the tunnel air heater located upstream of the flexible wall can be used to heat incoming air during propulsion cycle operation to temperatures of up to 680°F for a limited time.

During propulsion cycle operation, all air through the tunnel exhausts through a muffler to reduce excessive noise emissions. The muffler, located inside the tunnel's circuit, is a concrete structure with a series of splitters and resonance chambers. It uses both sound-absorbing material and Helmholtz resonators to attenuate the noise. This muffler is connected to the tunnel upstream of the second cooler, and it exhausts upward into the atmosphere. A 24-foot-diameter swinging valve closes the exhaust opening during aerodynamic cycle operation. When rotated 90 degrees, it opens the exhaust duct and closes the return duct to convert the tunnel into propulsion cycle mode.

The 10- by 10-Foot SWT can operate at reduced pressure to simulate high-altitude flight. In its aerodynamic cycle, altitudes between 49,000 and 160,000 feet are possible, and altitudes between 56,000 and 87,000 feet are maintainable in the propulsion cycle. Two Cooper-Bessemer exhausters, located in a structure inside the tunnel circuit, can evacuate the tunnel to a pressure as low as 2 psia in the aerodynamic cycle. Each compressor is powered by an Ideal Electric 2000-horsepower synchronous motor. This evacuation system also can be used to simulate flow through an engine during inlet tests. The 10- by 10-Foot SWT is also connected to an alternative exhaust source that can bring the tunnel to about 0.7 psia (stagnation pressure).[61]

The 10- by 10-Foot SWT featured a modern control room with panels of analog controls and instruments when it was built. Its location in the structure connecting the test section to the office building is unchanged, but its controls and data acquisition systems have been continuously modernized over the years, and its current appearance bears little resemblance to its initial one. Although the process has evolved in recent years, test sequences were traditionally preprogrammed into a computerized control system, and data acquisition is fully automatic. Much of the data, as well as selected analytical results, were available in real time, and all data could be recorded, sent to the center's central computer system, and/or transmitted directly to a client's host computer.

A model's instrumentation can be extensive and include almost any combination of sensors to measure temperature, pressure, force, and engine-performance parameters. Test support systems include compressed air, a hydraulic power system, combustion air (separate from tunnel air), gaseous hydrogen and oxygen, kerosene-based liquid fuel, and electrical power. A schlieren system is available for flow visualization, and other flow visualization techniques can be used as well.

HISTORY

After the end of World War II, the American aeronautics community, including researchers, manufacturers, and the armed services, realized that the new technologies of jet propulsion, swept wings, and rocket-powered missiles were opening the door to unprecedented advances in aircraft performance. As early as April 1945, researchers at NACA laboratories had begun recommending that the agency build new supersonic tunnels to enable the needed research. The concurrent rise of the Cold War made it imperative for the United States to invest in the first-class research facilities that would enable it to master supersonic flight, particularly after the rocket-powered Bell XS-1 (later renamed X-1) proved that such flight was not only theoretically possible, but actually achievable under a pilot's control.

In-flight data from a series of research airplanes showed some significant discrepancies from wind tunnel tests run during their design, most seriously in the transonic and supersonic speed ranges. These data reinforced the belief of many researchers that new, advanced wind tunnels were essential if these flight regimes were to be exploited. Engineers in the NACA, Navy, and Air Force had confidence that large supersonic tunnels could be built, and each organization developed plans for a new supersonic research center, but they were well aware that the cost and power requirements would be enormous. Ultimately realizing that Congress would not fund separate massive construction projects for each, the NACA and the armed services took the unprecedented step of proposing "a unitary program to provide for the coordinated responsibilities of the Army, Navy, CAA, and NACA...."[62]

After considerable debate and revision, Congress passed the National Unitary Wind Tunnel Act of 1949, authorizing $136 million for three NACA tunnels, one at each of its laboratories. The act also authorized $100 million for the Air Force to build a new development center at Tullahoma, Tennessee, and $10 million for certain university tunnels. The NACA's funding was for an aeronautical tunnel with transonic and supersonic capabilities at the Ames Laboratory in Moffett Field, California; a tunnel for missile research at the Langley Laboratory in Hampton, Virginia; and a supersonic engine research tunnel at Lewis.[63]

Design of the 10- by 10-Foot SWT (referred to as LUPA at the time) began in February 1950, about four months after the passage of the Unitary Act. The engineering team, led by Abe Silverstein and Eugene W. Wasielewski, brought what they had learned from the evolution of the 8- by 6-Foot SWT to the drawing board and added new features to extend the capabilities of the 10- by 10-Foot SWT beyond those of any existing tunnel. Lessons from the 8- by 6-Foot SWT included the usefulness of being able to run in both open- and closed-circuit modes, the effective design of its flexible-wall nozzle, the reliability and efficiency of having the compressor inlet in a large plenum, the practicality of the large desiccant air dryer, and the necessity of an exhaust muffler. The 10- by 10-foot SWT would, however, have a test section slightly more than twice

the cross-sectional area of the 8- by 6-Foot SWT, and it would need to have a top speed approximately 75 percent above that of the smaller tunnel.[64]

While the new tunnel would be somewhat more efficient than its predecessor, these performance requirements dictated that the 10- by 10-Foot SWT have approximately three times more power than the 8- by 6-Foot SWT—some 250,000 horsepower, more than any other wind tunnel.[65] The wide range of desired speeds (Mach 2.0–3.5) meant that test speeds up to Mach 2.5 would require no more than two-thirds the power needed for Mach 3.5. To reduce operating costs, the engineers decided to split the drive system and use two sets of motors driving two compressors instead of one. This required very careful analysis of the compressors and motors to be sure that the tandem compressors would function stably and productively together. During the process, they decided to include a bypass duct around the second compressor to keep it out of the airstream when it was idle. The use of dual compressors was uncharted territory, but the design proved to be very successful. (NASA's only other wind tunnel to use multiple compressors is the Unitary Plan Wind Tunnel at Langley, though its arrangement is very different from the 10- by 10-Foot SWT.)

The 10- by 10-Foot SWT's design improved on the 8- by 6-Foot SWT in a number of supporting areas. The flexible nozzle had a wider speed range and improved accuracy, and the adjustable second throat improved the tunnel's efficiency. Its greater cooling capacity provided better temperature stability, and the larger air dryer allowed longer propulsion cycle runs between regeneration periods. The engineers also streamlined the model preparation shop and model handling into and out of the test section by including a test section elevator and an overhead crane.

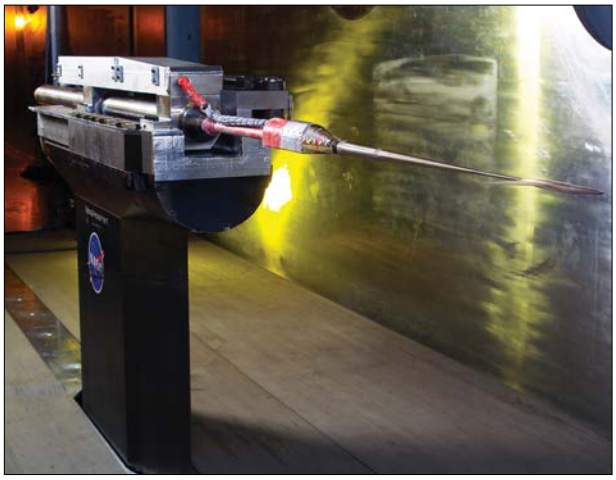
The 10- by 10-Foot SWT's design and construction coincided with the introduction of some of the first production models of practical electronic computers, and the engineers included some from the start to obtain the best possible data acquisition and analysis capabilities. One of these machines was an IBM 704 Data Processing System, the first mass-produced computer to combine core memory, vacuum-tube logic, stored programs, and the ability to perform floating-point-arithmetic computations. The NACA-developed Digital Automatic Multiple Pressure Recorder (DAMPR) automatically digitized pressure sensor signals at the then-astounding rate of 30 per second and transmitted them to Lewis's Central Automatic Digital Data Encoder (CADDE), which was located in the UPWT's office building. Elsewhere on the laboratory property was an Engineering Research Associates (ERA) 1103 computer to perform posttest data processing. Being a couple of years older than the IBM 704, the ERA 1103 was a more-primitive computer, but it was successful and quite useful at the time.[66]

After three years of construction, the $30 million UPWT was completed in 1955, and a series of trial and calibration runs began as soon as it was ready to run. Actual testing began later that year with a program to examine the inlets for the supersonic Convair B-58 Hustler bomber's General Electric J-79 engines. The program validated Convair's variable inlet design concept, but it suggested further improvements that

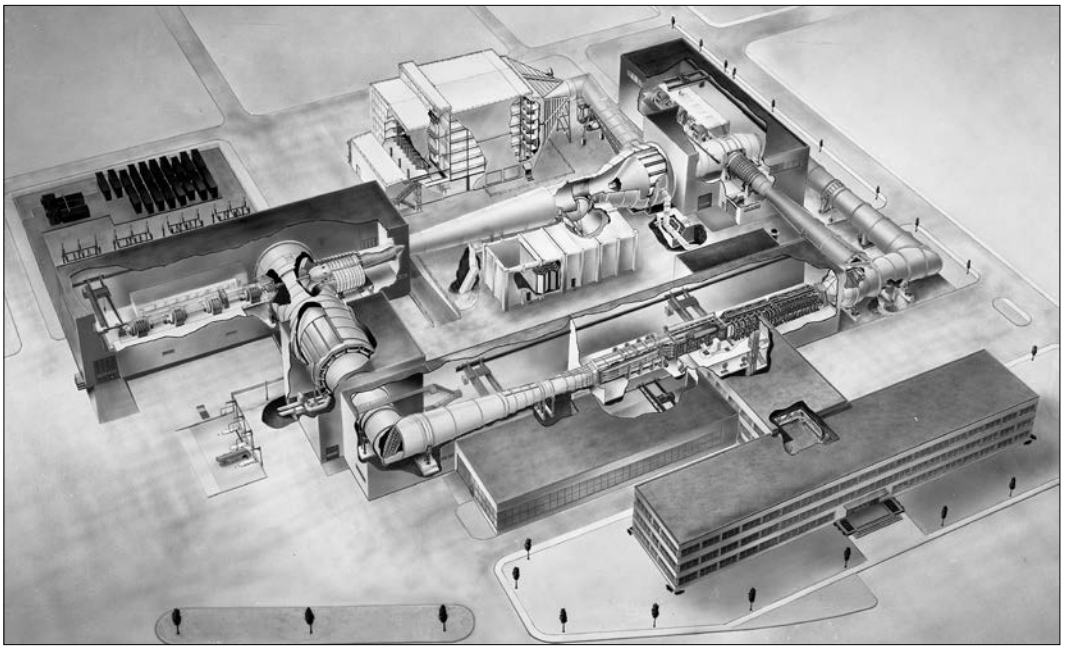
helped streamline the aircraft's development. Since that first test program, the 10- by 10-Foot SWT has hosted a variety of programs ranging from ramjet inlet performance to powered tests of the Space Shuttle stack.[67]

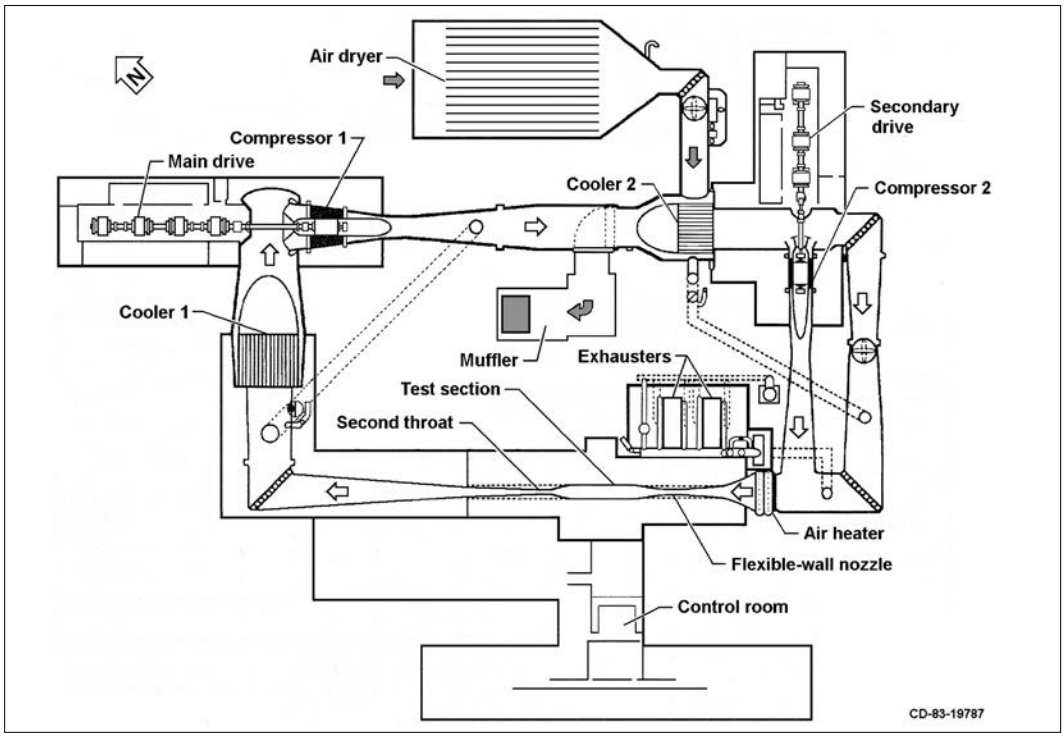
The 10- by 10-Foot SWT has received a number of modifications to improve its performance and flexibility over the years, and one major rebuilding in 1990 included the rewinding of all seven drive motors. A rise in the demand for subsonic testing during the 1990s led engineers at Lewis to investigate whether the 10- by 10-Foot SWT could be operated subsonically. These investigations and comparison tests in the 8- by 6-Foot SWT confirmed that the 10- by 10-Foot SWT would operate in a stable and predictable manner in the Mach 0–0.36 range, opening a new market niche for the tunnel. The tunnel was connected to the central exhaust system decades ago. An additional capability was demonstrated in 2003 when its exhausters were operated in a seven-stage configuration.[68] This lowered the tunnel's pressure and reduced the maximum dynamic pressure on a model to approximately one-half of its minimum using only the tunnel's two exhausters. While such a huge commitment of center resources makes such operations rare, they are useful for studies of planetary entry devices.[69]

On 15 October 1994, NASA and Lewis took an unprecedented, and thus far unrepeated, step by renaming the 10- by 10-Foot SWT to honor the long and distinguished career of Abe Silverstein. Silverstein joined the NACA as an engineer in 1929, was instrumental in the early development of the laboratory and propulsion research, and completed his NACA/NASA career as director of Lewis Research Center in 1969. The versatile tunnel, still primarily referred to as the 10- by 10-Foot SWT, remains in service with a bronze plaque in the tunnel's lobby that details the honoring of Silverstein. Because of its contributions to the Space Shuttle Program, the 10- by 10-Foot SWT was determined to be eligible for listing on the National Register of Historic Places in 2007.[70]



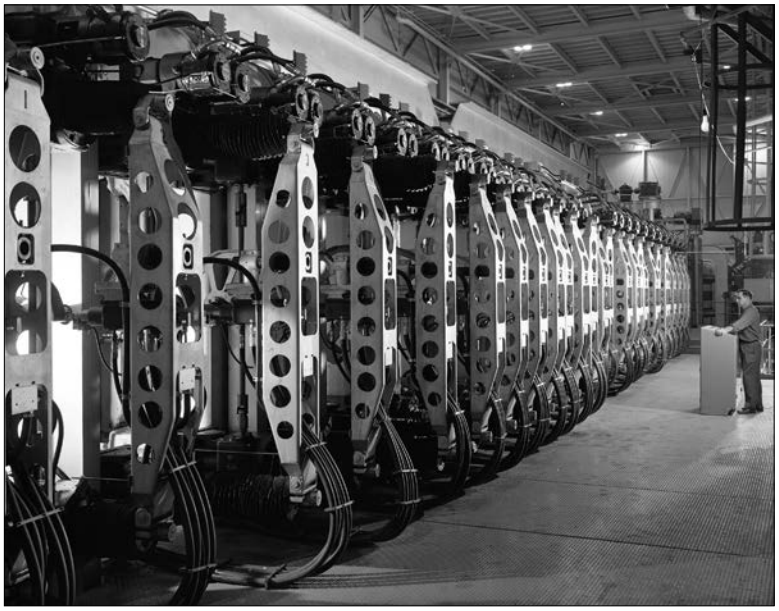
These small models were among several designs used in sonic boom studies that were conducted in the 10- by 10-Foot SWT during the 2000s. Strategically placed microphones detect the overpressure that humans hear as a boom when planes fly past faster than Mach 1. These studies have suggested ways to soften the effect considerably. (Photo credit: NASA GRC-2005-C-00948)



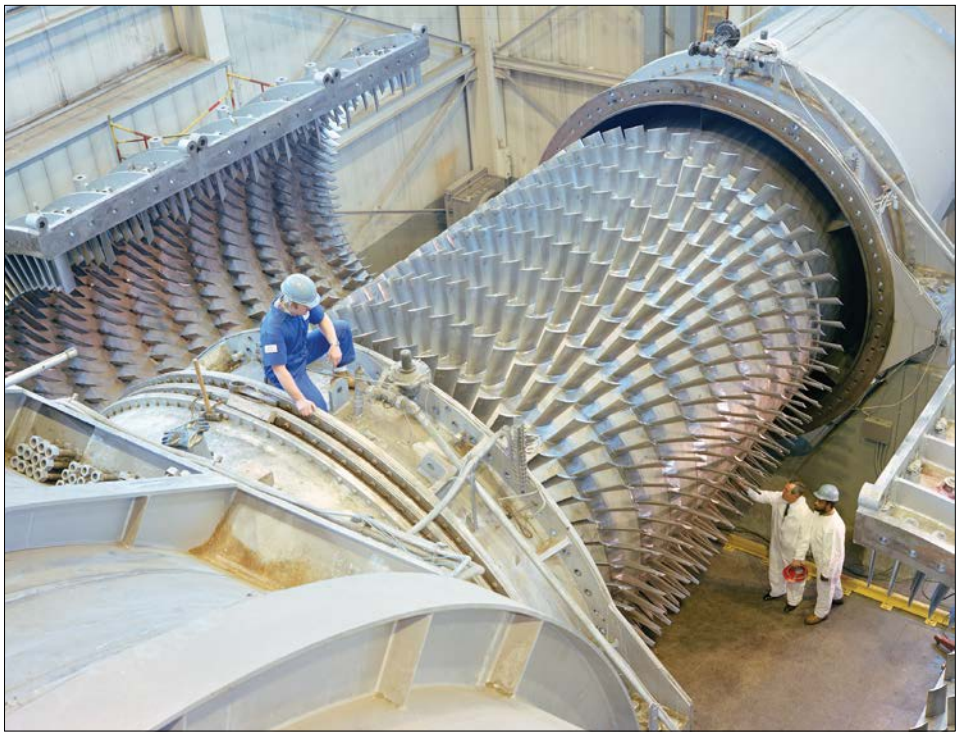


This cutaway rendering (top) and labeled drawing (bottom) reveal the complexity of the 10- by 10-Foot SWT. The dual-drive arrangement is unique within NASA, and it is the world's most powerful wind tunnel drive. (Image credits: NASA GRC-1957-C-44843 and NASA CD-83-19787)

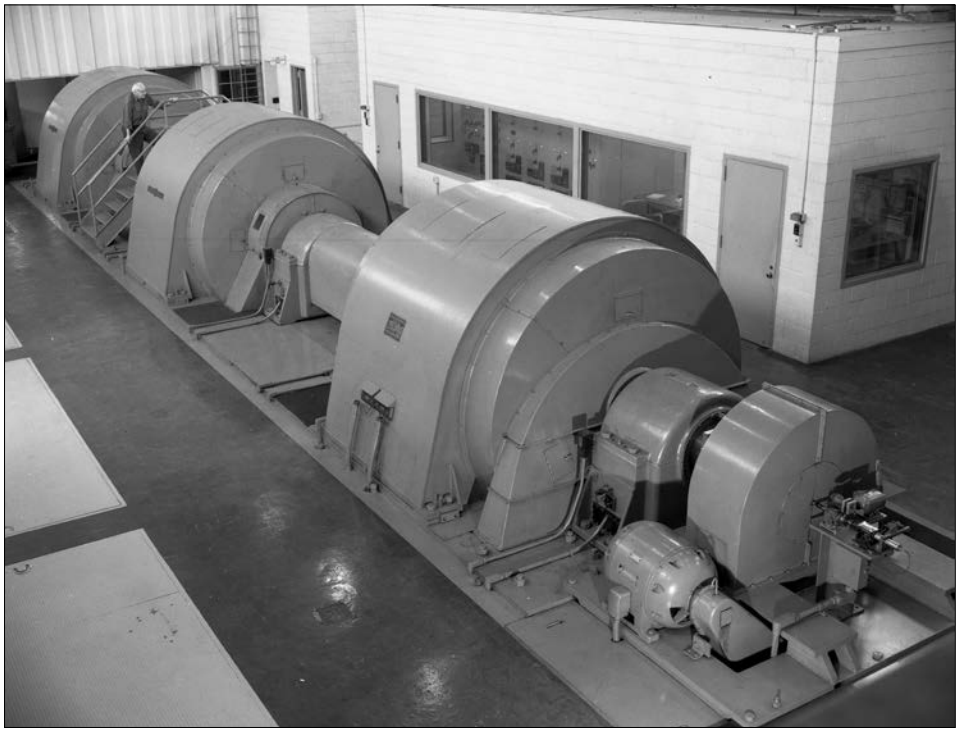
This nozzle interior view shows the right side wall distinctly curved and the left wall almost flat. Note the man's shadow and multiple reflections in the polished walls. (Photo credit: NASA GRC-1956-C-42059)



This jacking system adjusts the 10- by 10-Foot Supersonic Wind Tunnel's flexible nozzle walls to the contours needed for different supersonic speeds. Each side wall has a jacking system. (Photo credit: NASA GRC-1956-C-40936)



Compressor Number 2 (above) and its trio of 41,500-horsepower drive motors (below) illustrate the size of the 10- by 10-Foot Supersonic Wind Tunnel's drive. The compressor stator case is open for inspection and maintenance. Compressor Number 1 is similar, though it is driven by four of these motors. Altogether, the seven motors can deliver a total of 290,500 horsepower. (Photo credits: NASA GRC-1984-C-00615 and NASA GRC-1976-C-04494)



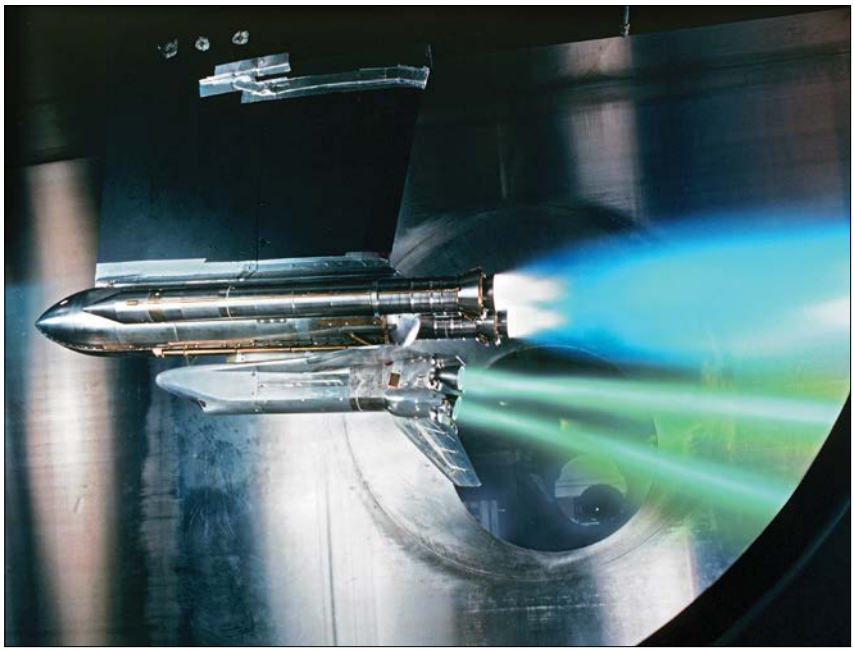
The 10- by 10-Foot Supersonic Wind Tunnel's air dryer, shown here during construction in 1955, is one of the largest ever built. Note the personnel door at its left corner for a sense of its size. (Photo credit: NASA GRC-1955-C-37670)

This 24-foot-diameter door swings to change the 10- by 10-Foot Supersonic Wind Tunnel from open- to closed-circuit operation. (Photo credit: NASA GRC-1956-C-42070)

Most of the panels seen in this early view of the Unitary Plan Wind Tunnel's control room have since been replaced with computer consoles. (Photo credit: NASA GRC-1955-C-40252)

The Unitary Plan Wind Tunnel was an early user of the IBM 704 Data Processing System to analyze large volumes of test data. The facility's computer power has been upgraded frequently. (Photo credit: NASA GRC-1959-C-51337)

The 10- by 10-Foot Supersonic Wind Tunnel's capabilities are illustrated here by 1977 aerodynamic cycle tests of an A-12, the precursor to the SR-71 Blackbird (top), and 1988 propulsion cycle tests of the Space Shuttle stack (bottom) with the main and solid rocket booster engines burning. The rocket plumes have both thermal and aerodynamic effects on the vehicle. (Photo credits: NASA GRC-1977-C-04657 and NASA GRC-1988-C-04806)



ENGINE RESEARCH BUILDING WIND TUNNELS

A 2006 aerial view of the Engine Research Building, with the Altitude Wind Tunnel/Space Power Chambers visible in the background. The network of circular ducts is part of the Central Process System that provides compressed air and exhaust vacuum service throughout Glenn Research Center. (Photo credit: NASA GRC-2006-C-01479)

SIGNIFICANCE

The Engine Research Building (ERB), one of the earliest research facilities built at the Aircraft Engine Research Laboratory (AERL) in Cleveland, Ohio, is a multipurpose structure with numerous laboratories, shops, offices, test cells, and wind tunnels for research into virtually every facet of aircraft engine design. Though numerous small wind tunnels have been built and operated as part of specific research programs over the years, certain tunnels in the ERB have had unique or particularly significant capabilities. The facility's main tunnels have been blowdown-type tunnels powered by air systems within the ERB and later supplemented by center-wide compressed air and vacuum systems.

Designed to be flexible and adaptable, the ERB has seen numerous modifications and managerial reorganizations since its opening in 1942, and its wind tunnels remain a valuable resource for studies of heat transfer, turbomachinery aerodynamics, and flow physics.

DESCRIPTION

The ERB is a large, mostly two-story masonry structure with a basement that has the external appearance of an industrial factory with an attached office building in front. In plan, it is essentially rectangular, measuring approximately 480 by 350 feet, plus a 130- by 65-foot extension from its southeast corner, making it the largest building at Glenn Research Center. Its parapeted flat roof is decorated by a plethora of ducts, pipes, exhaust fans, and penthouses. The larger ducts and pipes are connected to other facilities

and form part of the Glenn's Central Process System (CPS), a center-wide network of compressed air and vacuum ducts that employ compressors located in a central building and the various research facilities as prime movers. Unique among NASA centers, the CPS furnishes both air and vacuum at several pressures to all major research facilities. The office sections have rows of almost continuous windows, while the east and west walls of the Center Section have windows spaced somewhat wider apart. The building has doors on all sides, with its minimally adorned main entrance on the north face. Several electrical transformers and tanks for storing liquids or gases are distributed around the ERB's perimeter.[71]

The Center Section, Southeast Wing, Southwest Wing, and Northwest Wing have a basement that houses the equipment, the piping, the ducts, and some of the electrical gear that furnish utility services to most of the building. The largest machines, including air compressors (40, 125, and 450 psi), exhaust blowers, and two chillers for drying air, are located in the Center Section. They form the core of systems that provide service air, combustion air, dried compressed air, cooled low-pressure air, atmospheric exhaust, altitude (nominally 3 inches of mercury absolute) exhaust, water, and electricity at several voltages. Approximately 100 test setups in the building utilize these services, most of which are also connected to the CPS.

Most of the ERB's testing machinery, including wind tunnels, is on the first floor, with the six largest test cells located in the West Wing. Wind tunnels are distributed throughout the Center Section, West Wing, and Northwest Wing, with one in the Southeast Wing. The Center Section, Office, and Southwest Wing Extension have a second floor, though some of the test cells are high-bay areas that extend through the second level to the roof.

HISTORY

When the NACA decided to open a new research laboratory for investigations into engine performance and reliability, the challenges presented were very different from those posed by aerodynamic questions. Aircraft and engines could both be examined as a whole assembly, or specific parts could be studied, but there the similarities diverged. Almost all aerodynamic tests of wings, empennages, nacelles, or fuselages could be run in wind tunnels, but engine performance, including the performance of components such carburetors, pistons, and crankcases, not to mention that of fuels and lubricants, needed facilities other than wind tunnels. Materials and chemistry tests required facilities more akin to university laboratories. As noted in the Altitude Wind Tunnel chapter, many heat-transfer and cooling tests were suited to wind tunnels when an entire engine and propeller assembly was involved, but heat-transfer testing of individual components was better suited to far smaller tunnels.

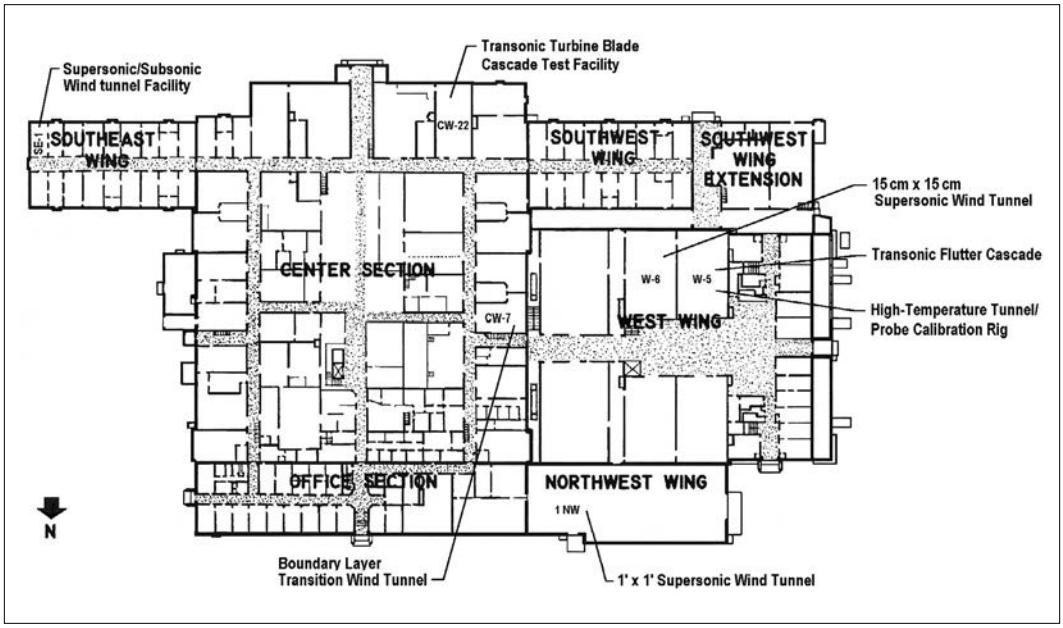
To address these, and other, issues of engine research, one of the original structures at the AERL was the ERB, which was assigned Building Number 5. It had been the core building for the laboratory since the first discussions about the AERL in 1939. The ERB was

designed as a large structure to house a varied assortment of specific laboratories; engine test cells; offices; and supporting air, water, and exhaust utilities. With inputs from engineers representing all areas of engine design and operation, Smith J. DeFrance (replaced by Ernest G. Whitney in 1940) and the design team at the NACA's Langley Laboratory wrestled with how to satisfy all of these needs in a single building. They decided to design it around a central structure with its corridors arranged to permit several options for future additions, something that proved very wise. This central section would have a basement to house a 1,500-ton (18 million British thermal units per hour) ammonia chiller (later replaced), numerous blowers, air compressors, and other supporting equipment without interfering with the research facilities, but with direct access to most of them. The object was to provide a structure that was flexible enough to address the current needs, but also permit reasonable modifications to spaces when those needs changed. To accomplish this, many of the ERB's rooms were fitted with bedplates capable of supporting a variety of machines, and with all feasible utility services.[72]

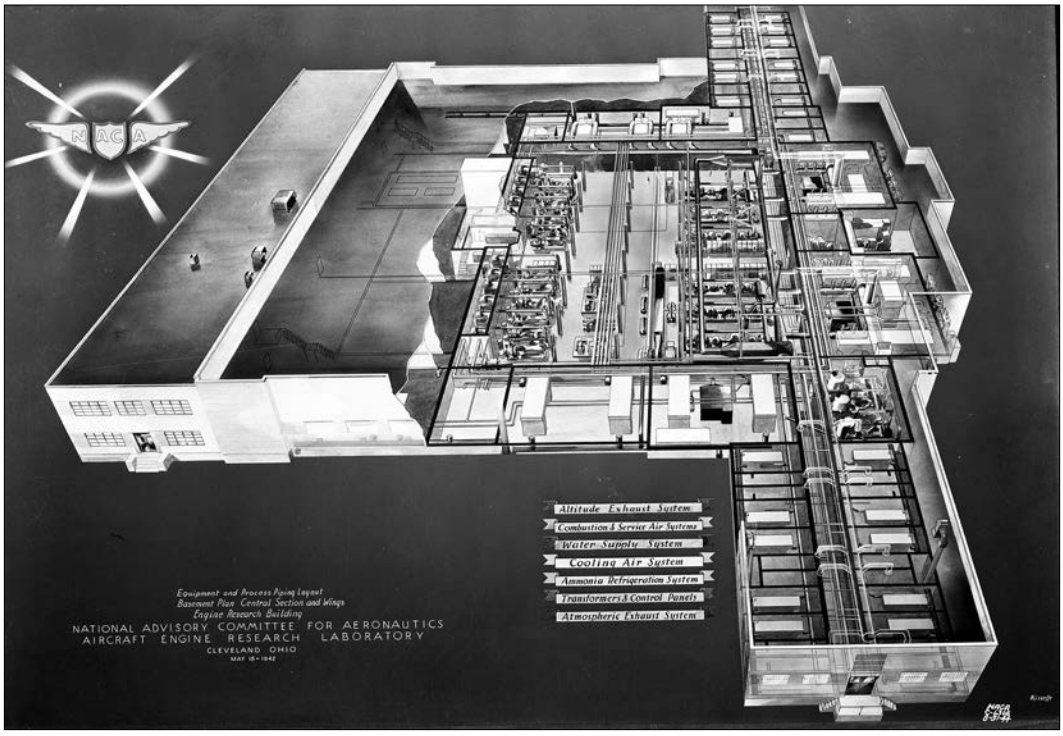
The ERB was designed and built on what is today called a "fast track," in that construction began before all aspects of the design were complete. The Center Section, with its support equipment and basic laboratories, was designed first, and the Sam W. Emerson Company began construction in January 1942 as the architects and engineers continued to design three wings: the Office Section on the north side and the Southeast and Southwest wings, both of which contained offices and smaller rooms for component investigations. Enough of the Center Section was completed by late 1942 for occupants to begin moving in. All of the original building was opened in 1943.

Even before the ERB fully opened in 1943, the first flight of the Bell XP-59 Airacomet, America's first jet-powered airplane, presaged significant changes in the work that would be done in the building, and they were only confirmed when a YP-59A, the second developmental model, became the first test subject for the newly completed Altitude Wind Tunnel in February 1944. Jet engine research would soon dominate the ERB's laboratories, and the vastly greater volumes of air handled by jets compared to piston engines made three additions essential. One was a large compressor and Turbine Research Facility Wing, which became better known as the West Wing. It contained six large test cells and more than a dozen smaller rooms, as well as additional air and exhaust machinery. The exhaust needs were supplemented by a second addition, the Northwest Wing, which housed four centrifugal exhausters and exhaust gas coolers. Themalller Northwest Wing entered service in 1946, with the West Wing following in 1947. The third addition was an extension to the Southwest Wing that added two altitude test chambers In 1947.[73]

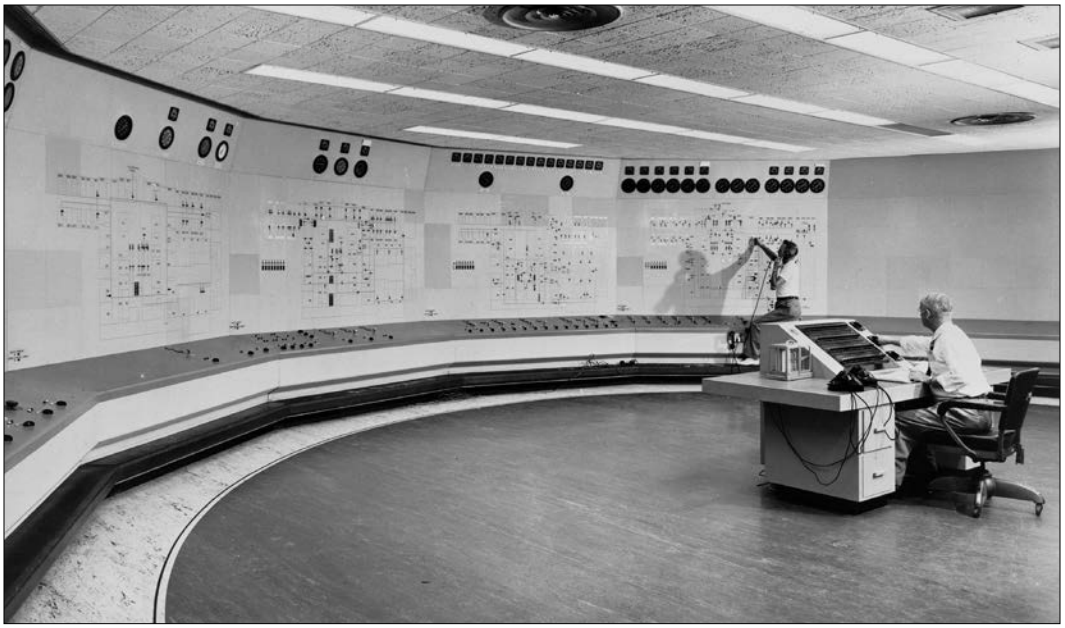
Since its opening, the ERB has proved the wisdom of its designers in making it a flexible structure. With at least 10 subsequent additions of major equipment, the ERB has continued to provide facilities that support cutting-edge research in combustion, heat transfer, turbomachinery, and advanced flow physics. The ERB continues in active service.[74]



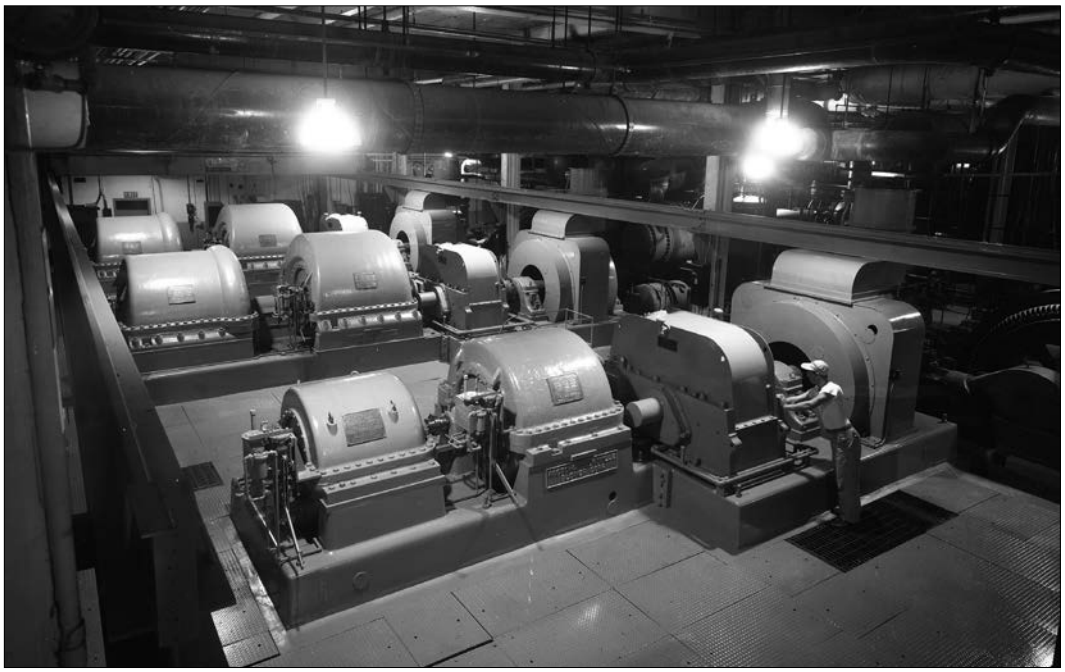
This 1967 plan drawing of the Engine Research Building's first floor shows the locations of its major wind tunnels. The structure originally consisted of the Center Section, Office Section, Southeast Wing, and Southwest Wing. The remaining wings were added within a decade. (Image credit: NASA GRC-ERB-2)



The various support systems and their equipment are shown in this cutaway rendering that exposes the Engine Research Building's basement as originally built. North is to the left. This drawing was made in 1942, before the West, Northwest, and Southwest Extension wings were built. (Image credit: NASA GRC-1944-C-06308)



All of the support systems in the Engine Research Building are managed from this control room. Much of this control panel has been modernized since this 1948 photograph. (Photo credit: NASA GRC-1948-C-21873)



These compressors, seen here in 1947, are part of the support equipment located in the basement of the Engine Research Building. (Photo credit: NASA GRC-1947-C-19605)

Wind Tunnels in the Engine Research Building

In addition to laboratories, altitude chambers, and test cells, the ERB has housed several wind tunnels during its life, many of them with unique capabilities. Some of these tunnels remain in service, while others have been dismantled or modified. Additionally, the ERB has hosted a number of small, specialty tunnels over the years, but these are considered to be "tabletop" tunnels and are not included in this study. In certain cases, the information available about a particular tunnel is imprecise or was not located, but the most significant tunnels that have been, or remain, in the ERB are briefly described below, listed in room-number order.

The ERB has a unique room-identification system. It is not totally consistent in style, but the following letters designate the different areas of the building, with the center's Real Property Office building numbers in parentheses:

C	Center (5)	SE	Southeast Wing (5)
CE	Center East (5)	SW	Southwest Wing (5)
CW	Center West (5)	SWX	Southwest Wing Extension (38)
NW	Northwest Wing (37)	W	West Wing (23)

1 NW: 1- by 1-Foot Supersonic Wind Tunnel

This 1955 general view of the 1- by 1-Foot SWT as originally built in Room 1 NW. Flow is left to right. The truss suspended from the ceiling supports the top plate used with all of the nozzle blocks. Two of the nozzle block elevator's vertical guide rails are visible below it. (Photo credit: NASA GRC-1955-C-40815)

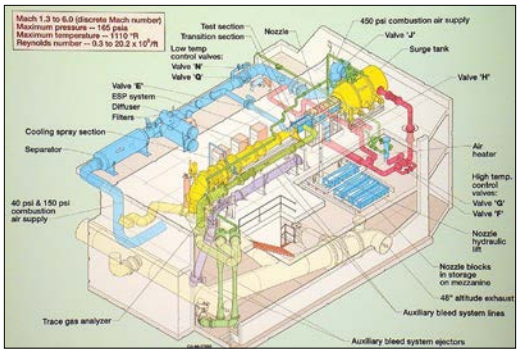
The 1- by 1-Foot Supersonic Wind Tunnel, also known simply as the "1 by 1," is the premier wind tunnel in the ERB. Opened in 1952, the 1 by 1 is currently one of the most active tunnels at Glenn, but it has endured significant periods of deactivation over the years, notably from 1960 through 1972 and from 1973 to 1980. It is an open-circuit tunnel powered by CPS air and altitude exhaust, so its run time is unlimited. Compressed air is primarily delivered at 40 and 150 psi dried to a dew point of –20°F. These flows can be combined and throttled to produce inlet pressures from 20 to 165 psi, the tunnel's limit.[75] Regulated by a set of remotely controlled valves, this air enters a plenum, or surge tank, which contains honeycomb and screen flow conditioners, and then passes through a nozzle to the test section.

A technician inspects a model mounted in the 1- by 1-Foot Supersonic Wind Tunnel's original test section in 1957 before closing the nozzle block. (Photo credit: NASA GRC-1957-C-45907)

The 1 by 1 can operate at 11 discrete speeds using interchangeable nozzle blocks designed for Mach numbers of 1.3, 1.6, 2.0, 2.5, 2.8, 3.0, 3.5, 4.0, 5.0, 5.5, and 6.0. Each block is 88 inches long. These nozzle blocks are stored on a movable carriage on a basement mezzanine directly below the tunnel. The carriage is positioned with the desired block over a hydraulic elevator, which then lifts the block through a floor opening and into alignment with the tunnel, where it is secured in place by bolting it to a fixed top plate that forms the ceiling of the nozzle. The same elevator returns blocks to the storage carriage. Exchanging nozzles takes 10–15 minutes. The Mach 6.0 nozzle was added later, along with a 665-kilowatt electric air heater needed to enable operation at that speed.

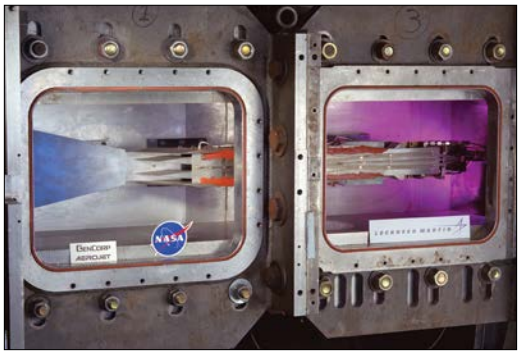
The hydraulic elevator is seen here in 1955 lifting a nozzle block from the basement mezzanine into alignment with the 1- by 1-Foot Supersonic Wind Tunnel. Eleven interchangeable nozzles are available, with a Mach number range of 1.3 to 6.0. (Photo credit: NASA GRC-1955-C-40817)

In 1997, engineers replaced the original test section with a longer one that features interchangeable window panels of steel and optically clear glass that are easily configurable for different test needs. Most panels span approximately one-half of the 53.25-inch length, but one panel, the "long wall," stretches the full length. It is a simple steel plate, so customers can make duplicates and mount models prior to arriving on site, and the wall easily bolts onto the test section frame, saving significant setup time. Air exits the test section through a transition and circular diffuser to the altitude exhaust system. A water spray cools the exhaust air to increase its density and improve the exhaust system's efficiency.



This phantom drawing of the 1- by 1-Foot Supersonic Wind Tunnel shows its major components and arrangement. Its 11 nozzles, with a storage area on the basement mezzanine and the hydraulic elevator to insert them into the tunnel, make this a very versatile facility. (Image credit: NASA CD-98-77865)

The 1 by 1 has a trace gas system using ethylene (C_2H_4) that can be injected to measure specific mass flow rates, or to determine the mixing characteristics of models. A pitot probe connected to a gas analyzer samples the exiting gas at selected points and determines its hydrocarbon content. The tunnel also has a bleed system to extract boundary layer air from selected portions of the test section side walls. A set of panels with different hole configurations is available, and they connect to the altitude exhaust system. One of the two connection lines includes a pair of air ejectors that can reduce the pressure to 0.5 inches of mercury absolute. Up to 576 pressure measurements can be sampled and recorded by an ESP system, and a variety of flow visualization systems are available, including schlieren photography, laser sheet visualization, oil-flow, and pressure-sensitive paint. The tunnel also supports high-speed dynamic data acquisition (Dewetron) and PIV.[76] Electric and hydraulic power for model actuators is also available. Two rooms adjacent to the tunnel house the control room and a shop for preparing models.



The 1- by 1-Foot Supersonic Wind Tunnel's current test section, installed in 1997, provides greater length, easier access, and better visibility than its predecessor. The nozzle block no longer has to be opened for access to the model. (Photo credit: NASA GRC-1995-C-01375)

The 1 by 1 is utilized both for basic research and for tests of specific designs of components such as inlets. A considerable portion of this work involves the development and validation of computational fluid dynamics code. The tunnel remains in active service.[77]

The 1- by 1-Foot Supersonic Wind Tunnel's control equipment, seen here in 1997, occupies this room adjacent to the tunnel room. (Photo credit: NASA GRC-1997-C-01780)

CW-7: Boundary-Layer Transition Tunnel

The Boundary Layer Transition Tunnel in Room CW-7 is seen in 1983. Flow is left to right. The return duct at right passes overhead to the settling chamber, which is out of view to the left. The test section is adjacent to the stool. (Photo credit: NASA GRC-1983-C-04097)

The Boundary Layer Transition Tunnel (BLTT) closed-circuit, low-speed tunnel, which opened in 1983, was built to study the relationship between heat transfer and laminar-to-turbulent-boundary-layer transition. Its circuit includes a 10,000-cubic-feet-per-minute blower, flow conditioning chamber, 6- by 27-inch test section, diffuser, damper, heater, filter, and cooler, and the pressure gradient across the 5-foot-long test section can be varied by adjusting the test section's top panel. The test section floor is the test panel. Overall flow is controlled by the damper to between 10 and 100 feet per second (6.8–68 miles per hour), and the heater and cooler provide temperature control between approximately 60 and 150°F. Screens with different percentages of open area are inserted in the flow conditioner to generate the desired level of initial turbulence. The BLTT uses static-pressure taps to identify the transition region and thin-film heat sensors to measure temperatures that indicate changes in the heat transfer rate. The test panels can be heated or cooled, and their roughness and contour machined as desired.

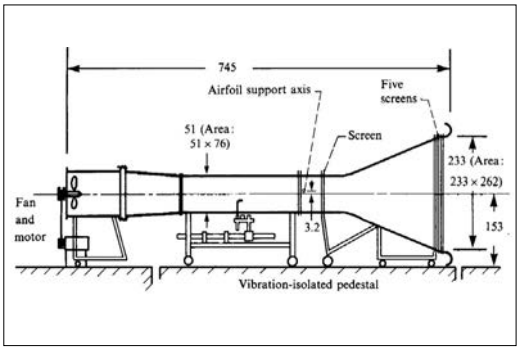
Investigations in this facility have contributed to the development of mathematical models used in computational fluid dynamics codes to predict the aerodynamics and heat transfer in turbine airfoils of gas turbine engines, based on obtaining physical understanding of the flow phenomena. The tunnel was used to study the aerodynamics of low-pressure turbine (LPT) airfoils and to conduct a seminal experiment demonstrated successful application of active flow control with plasma actuators to reduce the losses caused by flow separation. The BLTT remains in service.[78]

CW-13: 20- by 30-Inch Low Speed Wind Tunnel

View of the 20- by 30-Inch Low Speed Wind Tunnel in the Engine Research Building's CW-13 test cell. (Photo credit: NASA CW-13A)

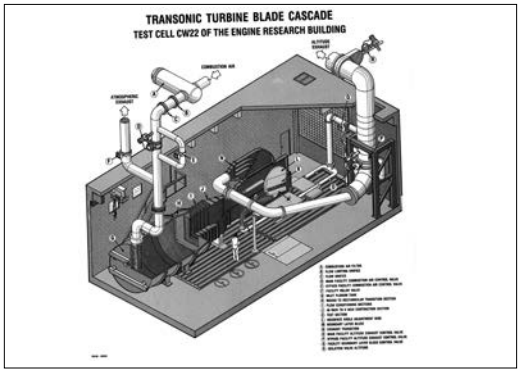
The 20- by 30-Inch Low Speed Wind Tunnel is used to study two-dimensional shear layer flow fields and flow separation and its control. The self-contained test rig includes a variable-speed 10-horsepower motor downstream that drives airflow from the large rectangular bellmouth through the 20- by 30-inch test section at speeds from 0 to 15 meters per second.

The 80-inch-long test section includes an opening in the bottom for probes and Plexiglas roof and side walls that permit a high-speed camera to capture flow visualization. Airfoils can be mounted on an upstream spacer section. A jet facility added to CW-13 can generate unheated supersonic jets up to Mach 1.5 and heated jets with low Mach numbers. CW-13 also includes Particle Image Velocimetry and Rayleigh Scattering.[79]



Side view of the 20- by 30-Inch Low Speed Wind Tunnel test section. (Image credit: NASA CW-13B)

CW-22: Transonic Turbine Blade Cascade Test Facility



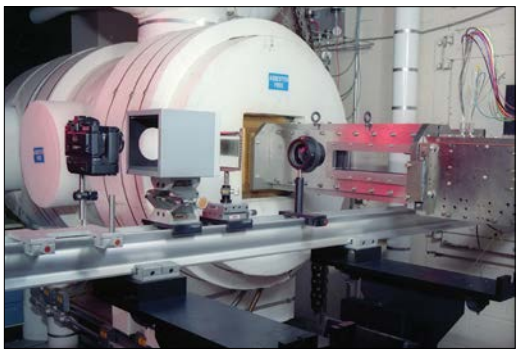
This 1992 drawing illustrates the parts and functioning of the Transonic Turbine Blade Cascade Test Facility in Room CW-22. Note how the disk "E" and turbine blades "D" can be rotated to change the blades' angle of attack, while the inlet boards "A," "B," and "F" move to accommodate the change. This unique tunnel is used to evaluate the aerodynamic and heat transfer characteristics of new blade airfoil designs. (Image credit: NASA GRC-1992-C-02846)

This unique tunnel was built to evaluate the aerodynamic and heat-transfer characteristics of sets of advanced turbine blade designs. Opened in 1991, the Transonic Turbine Blade Cascade Test Facility (TTBC) is an open-circuit tunnel that utilizes the CPS's combustion air and exhaust systems for power. Within in its 48-inch-high (maximum) by 6-inch-wide test section is a set of 10 parallel turbine airfoils mounted on a disk that can be rotated to change the blades' angle of attack and angle that they turn the air. The test section's top and bottom panels, known as "inlet boards," adjust vertically to accommodate changes in the disk's position.

The CPS supplies compressed air at 40 psi to the TTBC. Control valves and a flow-limiting orifice mounted above room CW-22 set the flow rate, and a circular duct conveys it down to the tunnel's 108-inch-diameter plenum. Air from the plenum passes through two transition sections, interspersed with a flow conditioner, and into the test section. The cascade of test blades turns the air nominally 132 degrees—infinitely adjustable between –30 and +15 degrees from that baseline—and directs it into an exhaust duct connected to the CPS. Adjustable test section side wall boundary layer extraction scoops are also drafted by the vacuum system. The scoops may be blanked off, or the extraction can be regulated with manual valves.

Tests in the TTBC usually involve measurements of temperatures and pressures, all of which are automatically recorded and displayed in the tunnel's control room. The TTBC's combination of approximately Mach 1 maximum inlet speed, high turning angle, and infinitely adjustable angle of attack make this facility unique, and it remains in service.[80]

SE-1: Supersonic/Subsonic Wind Tunnel Facility

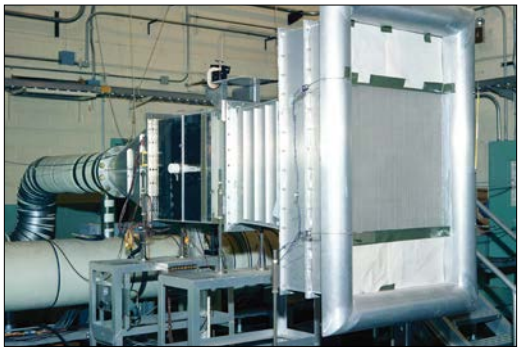


This view shows a portion of one of the two Supersonic/Subsonic Wind Tunnels located in Room SE-1 in 1993. (Photo credit: NASA GRC-1993-C-04780)

The Supersonic/Subsonic Wind Tunnel Facility (S/SWTF) was a pair of similar tunnels that could operate in both subsonic and supersonic modes. The two tunnels had the same 36- by 2-inch test sections and were very similar in most respects. Though both were blowdown-type tunnels that used the CPS's vacuum system, their primary difference was that Tunnel Number 1 had an atmospheric inlet, while Tunnel Number 2 used the CPS's 40-pound-per-square-inch combustion air system for its inlet air. Both featured an inlet plenum, nozzle, test section, and diffuser, but Tunnel Number 2's greater pressure differential gave it a higher maximum speed, Mach 3.0 versus Mach 2.5 for its sister.

These tunnels had a seeding system that permitted the use of particulate and volatile seeding materials, including combustible ones. A schlieren system was available for flow visualization, and both tunnels were used for the development of laser instrumentation, including open-beam laser fringe anemometry systems for unsteady supersonic flow applications. Other uses involved heat flux measurement and tests of pressure-sensitive coatings.[81] The S/SWTF was removed from SE-1 in the 1990s.[82]

W-5A-2: Heat Transfer Tunnel/Probe Calibration Rig



The 6- by 27-inch Heat Transfer Tunnel/Probe Calibration Rig, seen here in 1984, was one of two tunnels located in Room W-5. Flow is right to left. (Photo credit: NASA GRC-1984-C-02531)

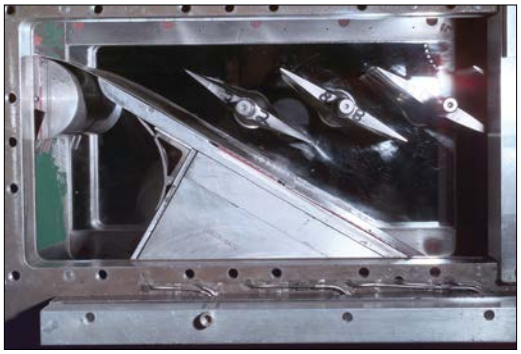
The Heat Transfer Tunnel (HTT) was an open-circuit tunnel with a 6- by 27-inch test section. It drew in atmospheric air through a flared inlet, screens, and a flow straightener. A contraction then passed it to the test section and out to the ERB's altitude exhaust system that served as the tunnel's drive. The pressure differential could produce a maximum test speed of approximately 100 miles per hour. As its name suggests, the HTT was used primarily to study how free-stream turbulence affects heat transfer from models, which could be equipped with electric resistance heaters. Temperature and pressure were the primary parameters measured and recorded by an electronic data acquisition system, with smoke and liquid crystal flow visualization equipment available as well. The HTT was also used to calibrate temperature probes used in other heat transfer facilities in the ERB.[83] The tunnel was removed from W-5A-2 in late 2019.[84]

W-5B: Transonic Flutter Cascade

The Transonic Flutter Cascade in Room W-5 was a unique facility for the study of turbine blade flutter in various situations. Flow is from top center to lower right, and the test section is adjacent to the raised platform. (Photo credit: NASA GRC-1980-C-03623)

The Transonic Flutter Cascade (TFC), also known as the Transonic Oscillating Cascade Facility, was a tunnel designed to study the aerodynamics and aeroelasticity of gas

turbine engine blades. Its primary investigations involved tests to understand and predict the onset of blade flutter in various situations, including stall flutter. Opened about 1990, the tunnel took in atmospheric air and used the CPS's vacuum system for power, and it could produce test speeds approaching Mach 1. Nine blades were mounted diagonally across the test section, which measured 3.85 inches in width by 29.1 inches along the "stagger line," the diagonal line of the blades across the test section. The stagger line was horizontal, and the airflow was inclined 30 degrees from horizontal, which was the nominal angle of the blades. Air was drawn in through a honeycomb flow straightener, through the test section, and out through a diffuser and control valve to the vacuum system. Immediately upstream from the row of blades, suction was applied through perforated walls to remove the boundary layer. Scoops in the top and bottom walls, known as tailboards, further reduced boundary-layer effects and controlled the static pressure of air leaving the blades. The chambers behind these extraction points were filled with fibrous material to minimize acoustic reflections.

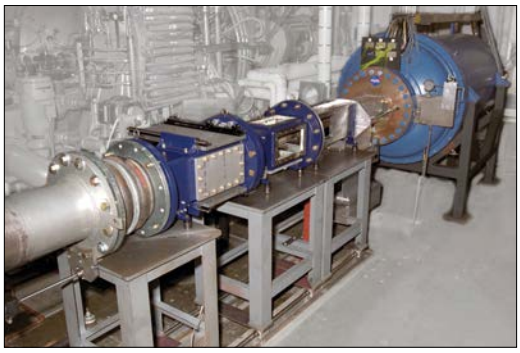


Part of the Transonic Flutter Cascade's test section showing three blades in 1999. The blades could be independently oscillated to simulate flutter and its related aerodynamic effects on adjacent blades. (Photo credit: NASA GRC-1999-C-00111)

The tunnel's most significant feature was that the nine blades, which were mounted on central shafts along their width, could be oscillated independently and in a controlled manner to simulate flutter oscillations. A 100-horsepower electric motor drives cams that oscillated the selected blades torsionally over a range of 1.2 degrees. The initial blade angles could be adjusted prior to a run. The primary instrumentation consisted of miniature pressure transducers on the upper and lower surfaces of selected airfoils with a minimum response frequency of 100 Hertz.

The TFC was modified over the years to improve its performance and address some unforeseen operational problems due to resonance issues that caused high low-frequency oscillations around Mach 0.8. The resonance problem was found to be the tuning of exit duct resonators, and they were tuned specifically for each inlet Mach number. In 2002, the test section was modified with a small offset at the stagger line to improve flow conditions. The TFC primarily hosted tests involving unsteady pressures and flows, especially as they relate to a phenomenon known as "fan blade stall flutter" that can cause significant fatigue problems in large turbofan blades. A major goal was validation of CFD codes.[85] The tunnel was removed from W-5B in late 2019.[86]

W-6B: 225-Square-Centimeter Supersonic Wind Tunnel



The 225-Square-Centimeter Supersonic Wind Tunnel in Room W-6B, seen here in 1998, is useful for a variety of studies, including the behavior of supersonic shock waves. (NASA GRC-1998-C-01784)

The 225-sq-cm Supersonic Wind Tunnel (SWT) is a small, open-circuit wind tunnel powered by the CPS's 40-pound-per-square-inch combustion air system and altitude exhaust system. Inlet air passes through a flow conditioning plenum, subsonic contraction, supersonic nozzle, and test section. Exhausting air travels through a fixed diffuser to the altitude exhaust system connection. The wind tunnel can be configured with one of three test sections: a 15- by 15-cm square test section, a 17-cm-diameter circular test section, or an octagonal test section.[87]

Basic pressure and temperature monitoring and recording are available. Other instrumentation available is a trace-gas system for flow tracking and mass-flow measurement, constant-voltage hot-wire anemometry, particle image velocimetry (PIV), and schlieren flow visualization.[88] A vacuum system for boundary-layer bleed is also in the process of being activated. Some of the more interesting tests performed in the 15- by 15-cm SWT have explored ways to manage shock wave boundary layer interactions using micro-ramps. Part of this investigation involves the development and validation of CFD codes that accurately predict this complex phenomenon. This tunnel remains in service.[89]

CW-5: Icing Physics Flow Laboratory

A NASA photographer aims a high-speed camera at the test section of the Droplet Imaging Flow Tunnel in the ERB in 2004. (Photo credit: NASA GRC-2004-C-00376)

The Icing Physics Flow Laboratory (IPFL)[90] was developed in the ERB in the mid-2000s to study the various aspects of fundamental physical processes that govern the formation of ice buildup on aircraft flying into supercooled liquid clouds. NASA Glenn's Icing Research Tunnel and Propulsion Systems Laboratory are used to investigate in-flight icing. Because

of the complex physics associated with icing, additional smaller-scale experimental facilities were needed. Until 2022, the IPFL was composed of two test facilities: the Droplet Imaging Flow Tunnel (DrIFT) and the Vertical Icing Studies Tunnel (VIST).

The DrIFT was an unrefrigerated open-loop facility for the visualization and characterization of water drop behavior, including impingement, splashing, and breakup. Originally designed for conducting aerodynamic studies, the DrIFT was modified for research into drop dynamics. The horizontal tunnel had a 6-inch by 6-inch test section suitable for testing instrumented airfoils up to approximately 6-inch chord. Optically clear test section windows allowed for high-speed imaging of the drop dynamics. Tunnel air flow (up to 175 mph) was generated by a single variable speed fan. A number of modifications have also been added to make the DrIFT more suitable for conducting drop studies.[91] The tunnel contraction was replaced with a new shape to prevent drops from breaking up prior to impingement on the airfoil in the test section; a new inlet screen was installed to reduce the turbulent intensity in the test section; and the test section was lengthened from 24 to 36 inches to improve upstream flow conditioning, increase droplet residence time, and allow for higher droplet velocities. A number of related systems such as a water drop generator, high-speed cameras, and timing systems have been developed and augmented the facility capabilities until it was decommissioned in 2022 to make way for a new Adaptive Icing Tunnel.

The Vertical Icing Studies Tunnel at Case Western Reserve University in 2006, just prior to its transfer to the Engine Research Building at NASA's Glenn Research Center. (Photo credit: GRC-2006-C-01117)

The VIST was originally developed under a NASA Cooperative Agreement with Case Western Reserve University and was moved to the IPFL in 2007. The VIST was designed to study the microscale physical phenomena associated with the initial stages of ice accretion. The facility produces a large, two-dimensional stagnation point boundary layer that is dynamically scaled to the stagnation point of a commercial transport wing. The test surface is a large flat plate 30 inches wide by 60 inches long. The plate is instrumented with heaters and thermocouples to study ice-induced roughness and heat transfer phenomena.[92] Additional measurement capabilities include infrared cameras to acquire surface temperature and traversable hot-wire anemometers to acquire boundary-layer velocity data. The facility also contains a spray nozzle used to inject water drops onto the test plate to study the water film dynamics and possible effects on boundary-layer transition.[93] The VIST capability remains in place in 2022.

PROPULSION SYSTEMS LABORATORY

This 1984 aerial view shows the original PSL with Test Cells 1 and 2 at the top, the Equipment Building and its connections to air and exhaust systems in the center, and the Engine Test Building addition, with Test Cells 3 and 4 at the bottom. (Photo credit: NASA GRC-1984-C-05499)

SIGNIFICANCE

The Propulsion Systems Laboratory (PSL) was the NACA's most advanced facility for testing full-scale gas turbine, ramjet, and rocket engines at simulated operational speed, temperature, and altitude. Building on technology first developed in the altitude test chambers at Lewis, the original PSL combined an atmospheric static test stand for engines with an altitude-simulating wind tunnel. A larger, more-powerful addition to the PSL embodies the original design principles, and it is NASA's sole facility with the capability to test full-scale engines under flight conditions.

DESCRIPTION

The PSL is a highly specialized type of wind tunnel. Instead of testing airframes and their components, the PSL was designed to evaluate the performance of reaction engines, those that generate thrust directly with an exhaust nozzle rather than a propeller. With the exception of true rocket engines, reaction engines move large volumes of air through the engines themselves, and the Brayton Cycle's compression-combustion-expansion process is sensitive to a number of factors. Thus, testing under in-flight conditions is an essential part of jet engine development and fundamental research.

The PSL was constructed in two major phases, although there have been numerous renovation and modification projects throughout its life. The original facility, opened in 1952, included an Access Building that enclosed Test Cells 1 and 2 (enlarged in 1957) and a Central Air Equipment Building (CAEB) that housed the air conditioning, supply, and exhaust machinery. An addition, completed in 1972, added another building for Test Cells 3 and 4, as well as expanded machinery in the CAEB, the addition of additional combustion air and exhaust equipment, and another structure for new air conditioning equipment. Test Cells 1 and 2 were closed in 1979 and, along with their heaters, coolers, and building, were demolished in 2008.[94]

Test Cells 1 and 2 were housed in a three-story, steel-framed building (Building 65) with corrugated, asbestos-cement panel walls and a flat roof. A continuous row of industrial windows on all four sides admitted ambient light at its upper level, and the main entrance door was centered on the northwest facade. The first floor had a shop area, which also contained the lower portions of the test cells and balance stands. The second floor was the primary working floor, and the thresholds of the test cell access doors matched its level. The test cells were arranged in parallel, and an adjacent control room contained the panels for operating each test cell, also called an altitude chamber, and test engine, along with data monitoring and recording equipment. Personnel here communicated with technicians in the CAEB's control room, since they operated the air systems that established the correct test conditions. A 1957 enlargement on the northwest side called the Access Building (Building 66) more than tripled the amount of shop space.

Test Cells 1 and 2 each included a tapered inlet section with straightening vanes, a 14-foot-diameter, 24-foot-long test cell, exhaust section, and diffuser, with the entire assembly measuring 100 feet in length. Constructed of steel plate and fabricated structure, each test cell was designed to operate under a partial vacuum to simulate altitudes as high as 50,000 feet (1.69 psia), and each featured a door that, when closed, made up one-half of the cell's cylindrical shell. The door was hinged to open upward and away from the center of the building to facilitate engine installation using an overhead crane, as well as setup and adjustment activities. Within each test cell, a mounting frame equipped to measure thrust held the engine. Each mounting frame's balance was anchored to the foundation below the test cell.

Both test cells could run in free-jet or direct-connect modes. The latter connected the inlet directly to the engine, and air passed only through the engine. In free-jet mode, air passed around and through the engine, thus including its inlet and exhaust nozzle in the test. Free-jet testing is particularly important for the supersonic flight regime, since the inlet must decelerate the air to a subsonic speed before it enters the engine's compressor.

The PSL's CAEB (Building 64), the largest structure of the complex, remains in service. It contains the compressors, exhaust blowers, refrigeration equipment, and other equipment needed to condition and supply air to the test cells. Its foundation and floors are constructed primarily of reinforced concrete, while its upper portion has a structural steel frame and brick walls. The basement houses ducting and auxiliary

equipment, while most of the main equipment is on the first floor. Heavy equipment is supported on pedestals that bear directly on the foundation for maximum stability. All mechanical and electrical equipment is managed from an elevated control room on the north side with direct visibility of all major machinery.

The CAEB's core machines are compressors and exhaust blowers. The main compressors are Elliott two-stage, centrifugal units with two primary and one secondary casing on a common shaft turned by a 16,500-horsepower motor. Each delivers 112 pounds of air per second at a pressure of 45 psi. The exhaust blowers are Roots-Connersville four-stage, centrifugal machines with two first-stage blowers on one shaft driven by a 10,000-horsepower motor, and one second-, third-, and fourth-stage blower on a second shaft turned by a 16,500-horsepower motor. Each of these blower sets can handle 550,000 cubic feet of air per minute. The expansion turbine for combustion-air cooling and compressors for delivering air at other pressures are also located in this building.

Between the test cells and the CAEB were an air dryer, three natural gas–fired air heaters, and the primary and secondary coolers that cooled the jet exhaust from as high as 3,500°F to approximately 150°F before passing it to the exhaust blowers. The primary coolers, one for each test cell, circulated water through hollow fins, and a spray cooler served as the secondary cooler. A cooling tower transferred heat absorbed by the water from the jackets and coolers to the atmosphere. The three-stage air dryer consisted of a pair of two-stage coolers using chilled water followed by a desiccant dryer with 190,000 pounds of activated alumina. The heaters provided air up to 700°F that was suitable for ramjets at high supersonic speeds, but cold air was needed for high-altitude, subsonic testing, and expansion turbines were soon added in the CAEB to cool ambient air by approximately 100 degrees. A pebble-bed heater for simulating hypersonic conditions was installed at a later date. All of this equipment was located outside. A separate, two-story, brick office building across Walcott Road completed the PSL complex.

The 1972 addition known as the Engine Test Building (Building 125) was erected southeast of the CAEB to house Test Cells 3 and 4. It has a structural steel frame and corrugated metal siding with a tan finish. The building is windowless, except for a single row of windows on the southeast facade that admits ambient light to a shop area. The main personnel entrance is an unadorned double door centered on the southeast facade, and large, roll-up doors are located on the southwest and northeast sides. A smaller building of similar construction houses combustion air conditioning equipment.[95]

Test Cells 3 and 4 operate very much like Test Cells 1 and 2, but at 24 feet in diameter by 39 feet in length, they are considerably larger than their predecessors, and they feature a number of different design details. Their access doors, which account for approximately one-half of the cylinder's circumference, roll around the backside of each cell to open. Their thresholds are at the level of the main floor. An overhead crane and monorail cranes fitted within the cells facilitate engine handling. A portion of each cell extends into a basement area and is supported on reinforced concrete pedestals. Each cell features an inlet plenum that can be configured for a wide range of test conditions and engines,

which are normally run in a direct-connect mode. Each cell has a carbon dioxide fire suppression system and is fitted with an Ormond six-component (three forces plus three moments for each of those axes) thrust stand capable of measuring thrust loads of up to 50,000 pounds and lateral and vertical loads of up to 15,000 pounds.[96] Test Cells 3 and 4 can operate at speeds of up to Mach 3 and 4 respectively and at simulated altitudes of up to 86,000 feet. Test Cell 4 also can be fitted with a palletized insert that allows limited testing at Mach 6. It uses a hydrogen burner and oxygen injection to furnish 100 pounds per second of vitiated air at 3,000°F to inlets of model hypersonic engines.

Unlike the parallel mounting of the original test cells, Test Cells 3 and 4 are arranged in a "V" pattern so that they both exhaust into a single plenum and cooler unit. This 50-foot-diameter, water-jacketed unit contains the primary cooler that employs hollow water-filled fins and the secondary spray cooler. Together they cool the exhaust gas from about 3,000°F to 90°F before it flows to the exhaust blowers, and the spray cooler also acts as a scrubber that removes a variety of potential pollutants from the gas stream. A cooling tower transfers this heat from the water to the atmosphere. The two 14-foot-diameter, water-jacketed exhaust ducts from the test cells are connected to the plenum portion of this unit. Since only one cell can operate at a time, a 14-foot-diameter, water-cooled davit valve swings 158 degrees to isolate the test cell not being run. To keep the same face toward the hot plenum in either position, the davit valve must rotate about its vertical axis as it swings. A technician rides on a small platform on the valve to control these motions, reaching the platform through one exhaust duct and exiting through the other. From the secondary cooler, a single 14-foot-diameter duct conveys the cooled exhaust gas to the exhaust blowers in the CAEB, which is augmented as needed by the center's exhaust system.

The combustion air supply system for Test Cells 3 and 4 is much more complex than the original one for Test Cells 1 and 2. Additional compressors and exhaust blowers were installed in an addition to the CAEB, and a separate new structure housed additional heating and cooling equipment. Compressors in the CAEB supply air through four ducts at different temperatures and pressures. These flows are blended into one main flow, passed through a rust separator to remove fines, and conveyed to one of the test cells; but some, or all, of it is usually heated or cooled to suit the needs of the particular test program. For cooling, a high-pressure supply duct is connected to one, two, or three expansion turbines connected in parallel. This cooled air (–60°F for Cell 3 and –90°F for Cell 4) is blended into, or becomes, the main flow to the test cell.[97] Heating is accomplished by routing part of the main flow through one or two heaters powered by afterburner-equipped Pratt & Whitney (P&W) J57 jet engines. This 1,200°F air is then blended into the main flow. The system allows either test cell to run with inlet air temperatures between –50 and 875°F.

The standard liquid fuel for engines being tested is Jet A/JP-5, which is stored in two 25,000-gallon, underground tanks. A centrifugal pump can deliver up to 200 gallons

per minute at 50-psi pressure. A gaseous hydrogen system is also available. Hydrogen, as well as nitrogen and oxygen, is supplied from trailers.

In 2012, Test Cell 3 was upgraded with an engine inclement weather capability to simulate engine operation in icing clouds at altitude. Ten spray bars are installed in the PSL-3 inlet plenum consisting of 222 individually selectable spray nozzles. The nozzle designs are similar to those used in the NASA Glenn IRT and are capable of being internally mixed using city or deionized water and service air to set a wide variety of cloud conditions. Both conventional icing and ice crystal clouds can be produced.[98]

A control room located on the main floor, to the left of the main entrance, contains panels that control and monitor both test cells and test engines. Directly above the control room is a data preparation room where the data acquisition and processing equipment is housed. Test parameters and sequences are executed by a preprogrammed, computerized process control system. Thousands of channels of data, including thrust, drag, lateral and vertical loads, fuel and air flows, pressures, temperatures, and a variety of other engine parameters, are measured by electronic instruments that transmit signals directly to the data acquisition equipment. The most significant test data are displayed on control room screens in real time.

HISTORY

The NACA built the Lewis Laboratory specifically for engine research, and most of its facilities have primarily been used for that work. The Altitude Wind Tunnel (AWT), one of the laboratory's first facilities, was designed and built with piston engines and propellers in mind. In fact, the engineers who designed it had no knowledge of the secret turbojet development work going on in Germany, England, and the United States. The AWT was well engineered, met its design goals, and contributed to making the last round of piston engines efficient and reliable, but in 1944, its first unofficial—and secret—test of a pair of General Electric (GE) I-16 turbojets in a Bell YP-59A Airacomet foretold the future of aircraft propulsion.[99]

While an excellent facility, the AWT quickly revealed that it was less than ideally suited for jet engine testing. Nevertheless, it and two static test stands for jets were soon booked well in advance. The NACA needed a facility that could produce airflows at the higher speeds and altitudes that jet aircraft would experience, and a facility designed for reaction engines, not engine-propeller combinations.

Lewis engineers immediately began to design a facility to meet this need. It came to fruition in 1947 as the West Wing addition to the Engine Research Building, which featured four altitude test chambers with diameters ranging from 30 inches to 10 feet. While they had numerous differences in detail, all of these chambers worked basically the same way. Each was powered by the pressure differential between supply and exhaust airflows produced by the building's central systems. The supply air was available at several pressures, and separate ducts delivered heated and cooled air. Each altitude test chamber included valves to blend the air sources and, thus, control the

air pressure, temperature, and flow into the chamber. Each chamber also included a gas-fired heater for additional heating of the supply air, which led to their area being termed the "four-burner" area." Individual jet-engine components, such as burners and nozzles, were typically tested in the smaller chambers, while the 10-foot-diameter chamber could accommodate entire engines. Researchers could set pressures equivalent to altitudes from sea level to over 50,000 feet and replicate thermal conditions the engine would encounter in flight. Leaving the test chamber, the exhaust entered a cooler that lowered the air temperature to maximize the exhaust system's efficiency, and a second set of valves that controlled the exhaust flow to maintain the desired pressure in the chamber. The "four-burner" test chambers proved the efficacy of this testing technique, but the rapidly growing field of jet propulsion made it evident that the NACA needed additional facilities.[100]

With the altitude test chambers in operation and their knowledge of jet engines and testing requirements growing daily, Ben Pinkel and his team of engineers at Lewis began to design a new facility that would build on the altitude test chambers' success, yet be more efficient, more productive, and able to test larger engines. Burns and Roe, a nationally prominent engineering firm, worked with Pinkel and his team to produce the final design drawings and specifications. In the process, the PSL's CAEB became the centerpiece of a laboratory-wide system now known as the Central Process System (CPS) to furnish compressed air, including combustion air for engine operation, and exhaust vacuum via a system of ducts. Similar equipment in other facilities, such as the Engine Research Building, also served the CPS, yielding a flexible, efficient system that is still able to serve a wide range of demands throughout the center.[101]

Congress approved almost $12 million for the PSL, and construction began in September 1949, with the Sam W. Emerson Company as prime contractor. Although it included several interconnected structures, construction proceeded smoothly, and the PSL was completed in September 1952. The following month, a Wright XRJ47 ramjet became the first engine tested in Test Cell 2. A few days later, the first test of a GE J73 turbojet inaugurated Test Cell 1.

The original plan was to construct the complex for Test Cells 1 and 2 in two phases, but the second phase became a series of smaller projects during the mid-1950s. These included another exhaust blower set and additions to the air dehydration unit in 1955, followed by the desiccant air dryer and the Access Building addition the next year. Although the basic arrangement of the two test cells remained unchanged over the years, the complex received numerous upgrades. Many of these involved control and data acquisition equipment, especially during the 1960s. Electronic pressure transmitters replaced manometers, and data acquisition became more computerized and automated. A closed-circuit television system was installed to provide a clear view inside the chambers during tests.[102]

Between 1952 and 1979, the dual test cells stayed well booked and tested no fewer than two dozen different turbojet, ramjet, and rocket engines, plus several components and

sub-assemblies. Key development work on the Pratt & Whitney RL-10 hydrogen-fueled rocket included substantial testing in Test Cell 1 during 1962–64. By the mid-1960s, however, it had become clear to the PSL staff and Lewis's management that the center needed not only the capacity to accommodate more test programs, but also the ability to test larger, more-powerful engines. The new, high-bypass turbofan engines, such as the GE TF-39 and P&W JT9D, produced more than 40,000 pounds of thrust, well beyond what the original test cells could handle.[103]

Lewis began construction of an addition to the PSL in 1967. The addition, known as the Engine Test Building, was designed around two test cells that had almost five times the internal volume of their predecessors and a wider range of test speeds, temperatures, and pressures for altitude simulation. Additional compressors and exhaust blowers were installed in the CAEB, and new expansion turbines and heaters for conditioning the combustion air were installed in a new building. The construction was completed late in 1972, but not before a test crew's improper actions seriously damaged the facility. On 7 April 1971, miscommunication between changing shifts led operators to start an exhaust blower without having opened a critical exhaust valve. The massive overpressure that quickly developed ruptured a 96-inch duct fitting in the basement, blowing the projectile up through the main floor and roof, leaving large holes. Two people were injured, but fortunately, no one was killed. The repairs and recertification were expensive and time-consuming, but in its wake, engineers and safety personnel made several equipment and operational changes to prevent a future occurrence.[104]

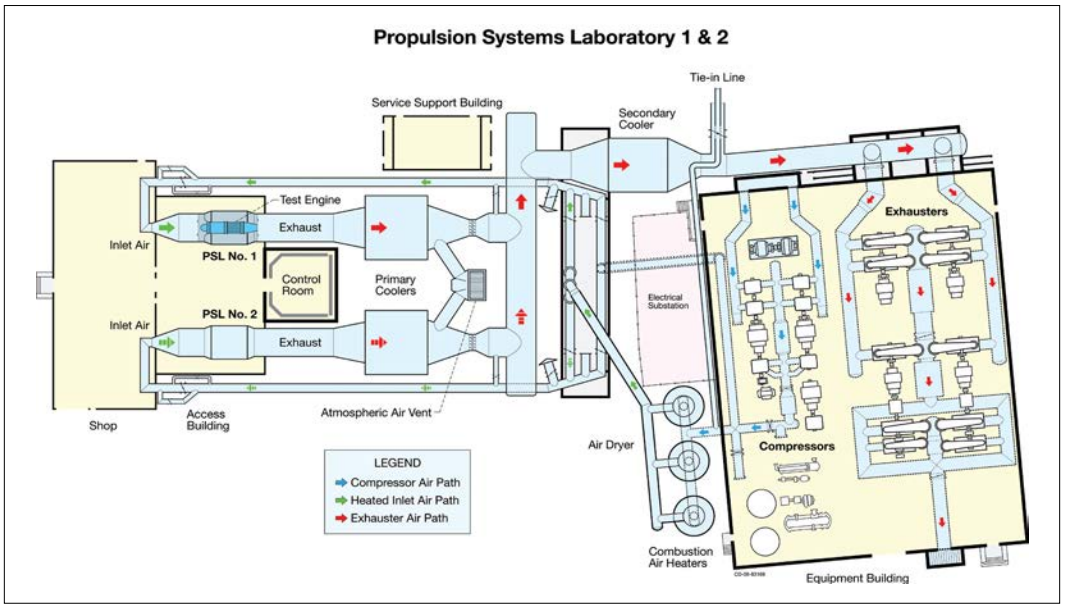
NASA embarked on a "Quiet Engine" research program in 1971, and one of the prototype turbofans became the first engine tested in Test Cell 3 beginning in November 1972. Test Cell 4 opened with a P&W J58 test program in July 1973. Since its opening, the facility has hosted test programs involving some of America's most innovative engines, including Pratt & Whitney's TF30, F100, and JT8D, among others.[105]

NASA's plans were to close Test Cells 1 and 2 after the newer test cells entered service, but demands for engine testing kept them reasonably busy through the 1970s. Nevertheless, the facility's size and age, along with budget cuts, made it increasingly difficult to justify operations in either of the original test cells, and Test Cell 1 saw its final test in 1979. With the test cells shut down, carpenters built temporary offices in between them that remained occupied for more than two decades. All the while, the test cells and the outdoor supporting equipment were not maintained and slowly deteriorated.

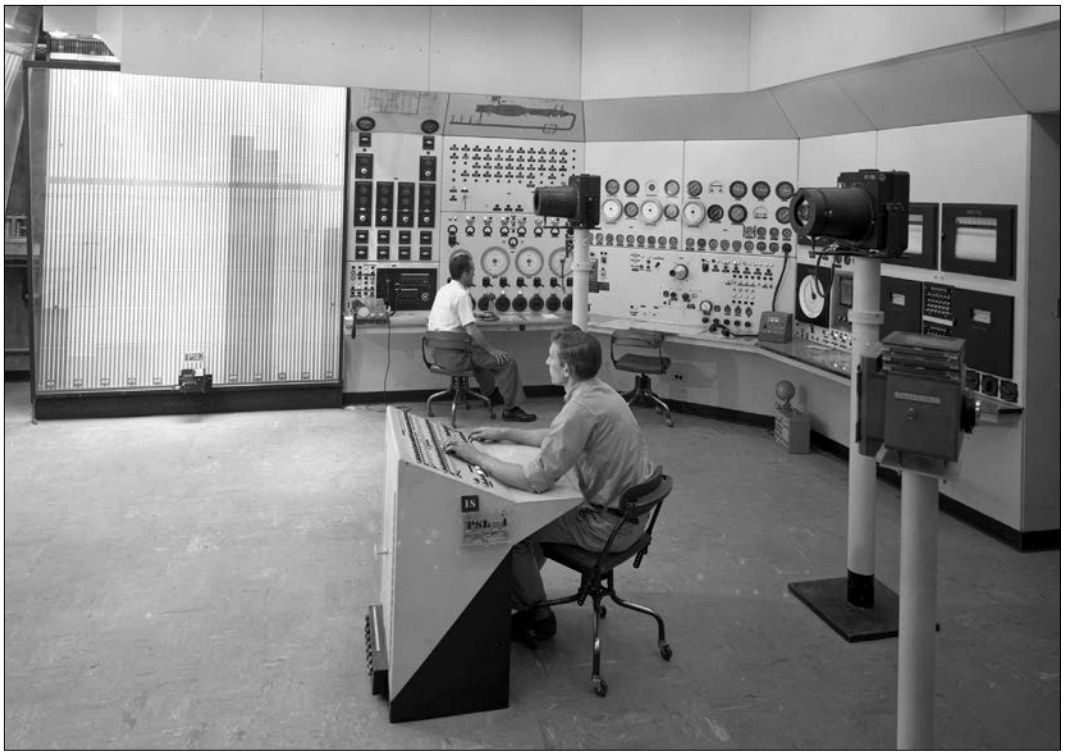
With support from NASA Headquarters, the renamed Glenn Research Center initiated plans to demolish all of the original PSL northwest of the CAEB. After four years of planning, community awareness meetings, and historical documentation, demolition began in late 2008 and was completed in 2009.

While the original test cells are gone, Test Cells 3 and 4, supported by the original CAEB, remain in active service. The facility is NASA's only resource for flight simulation of air-breathing reaction engines, and it continues to receive investments to maintain and improve its capabilities.[106]

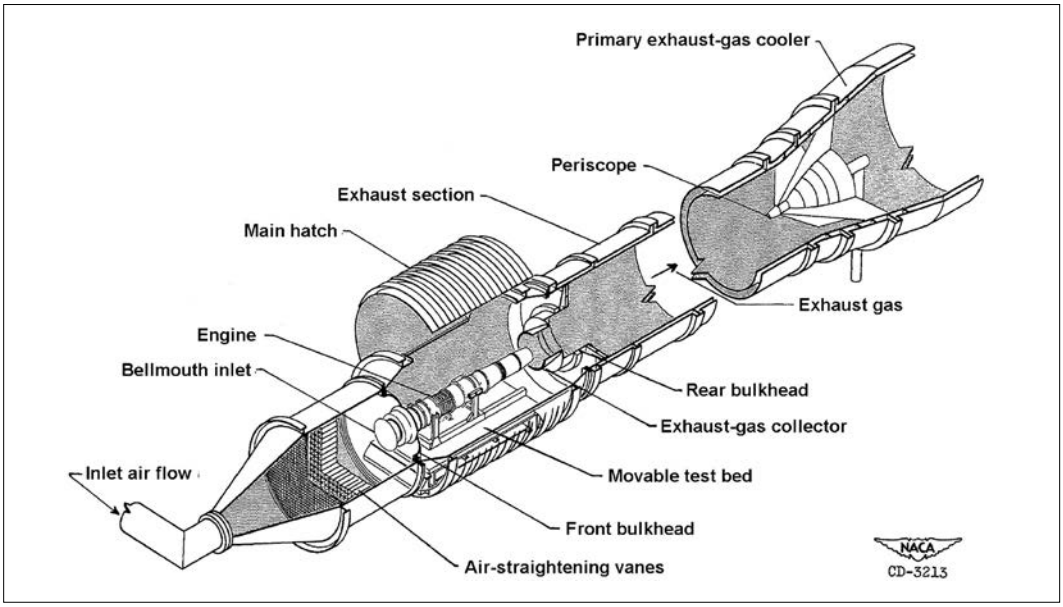
The original Propulsion Systems Laboratory, seen here in 1955, housed Test Cells 1 and 2 in the Access Building on the left. The primary exhaust coolers are in the center, with heaters on the right. The Equipment Building is behind the heaters. Note the angled air supply ducts to the test cells. (Photo credit: NASA GRC-1955-C-39961)



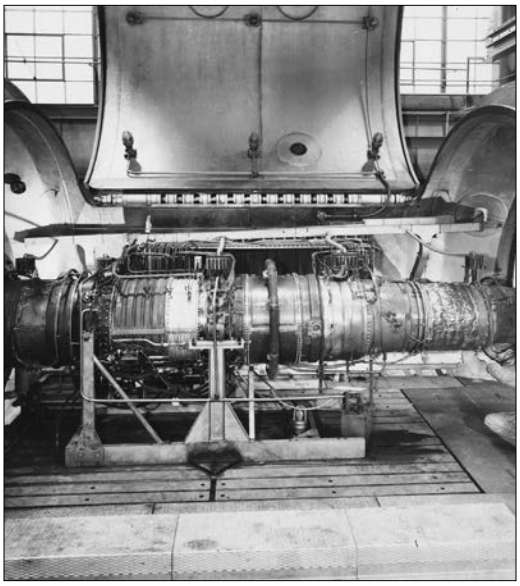
These Propulsion Systems Laboratory floor plans show the Access Building, including the “shop area” addition at the left, the coolers and heating equipment in the middle, and the Central Air Equipment Building at the right. (Image credit: NASA CD-09-83169)



Test Cell 2 was controlled from this panel in the control room, seen here in 1954. A mirror image of this panel in the same room controlled Test Cell 1. Note the cameras used to photograph multi-tube manometer panels (some not visible) so that pressures could later be read from the prints. (Photo credit: NASA GRC-1954-C-35900)

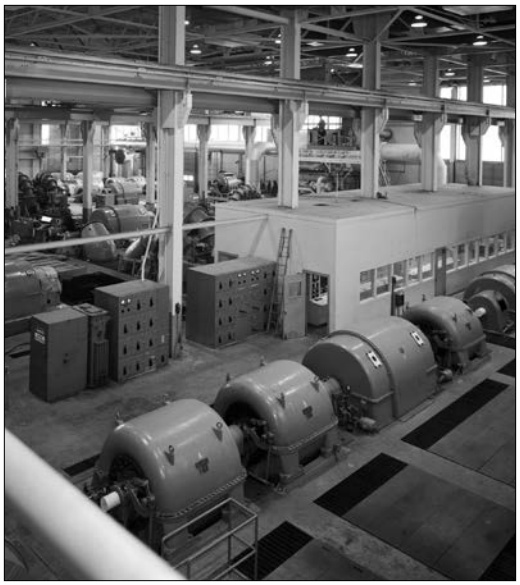


Test Cells 1 and 2 were essentially identical, but mirror-imaged, facilities with this configuration. The periscope allowed remote observation of a test in progress. The exhaust section had a water jacket, and most of it was located outside the Access Building. (Image credit: NASA CD-3213)



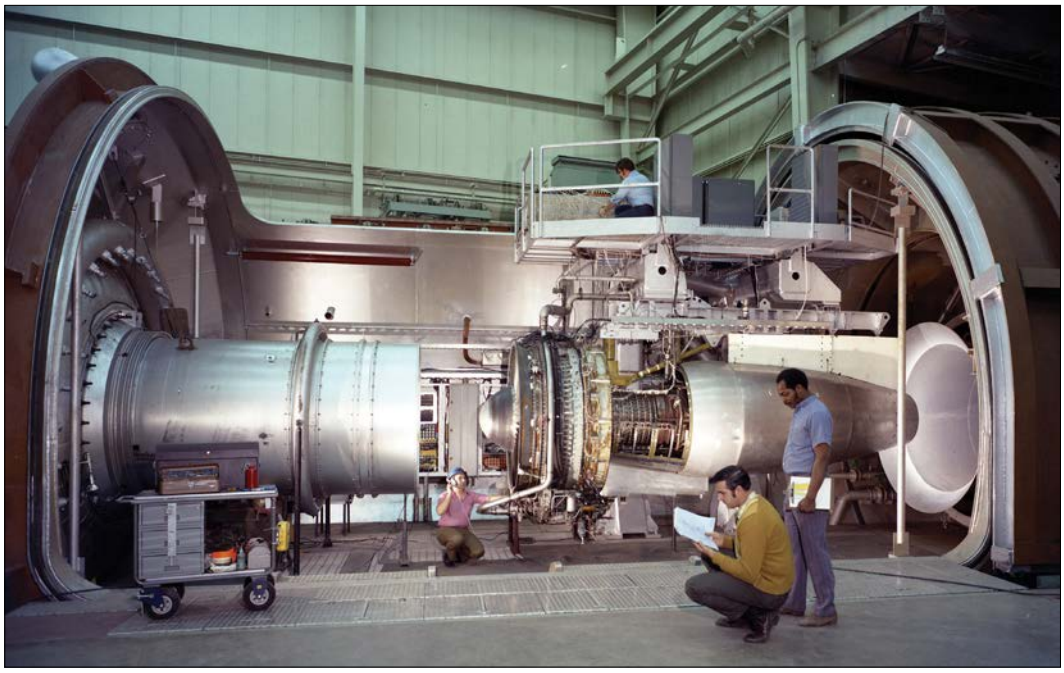
A General Electric J73 turbojet is shown here mounted in Test Cell 2 in 1952. This test cell could also be fitted with a small, enclosed wind tunnel that spanned the length of the cell. (Photo credit: NASA GRC-1952-C-31359)

This Roots-Connersville four-stage blower, seen here in 1955, was one of the original three that generated primary exhaust draft for the test cells. Located in the Equipment Building, these now serve Glenn's Central Process System as well as the Propulsion Systems Laboratory. (Photo credit: NASA GRC-1955-C-38383)

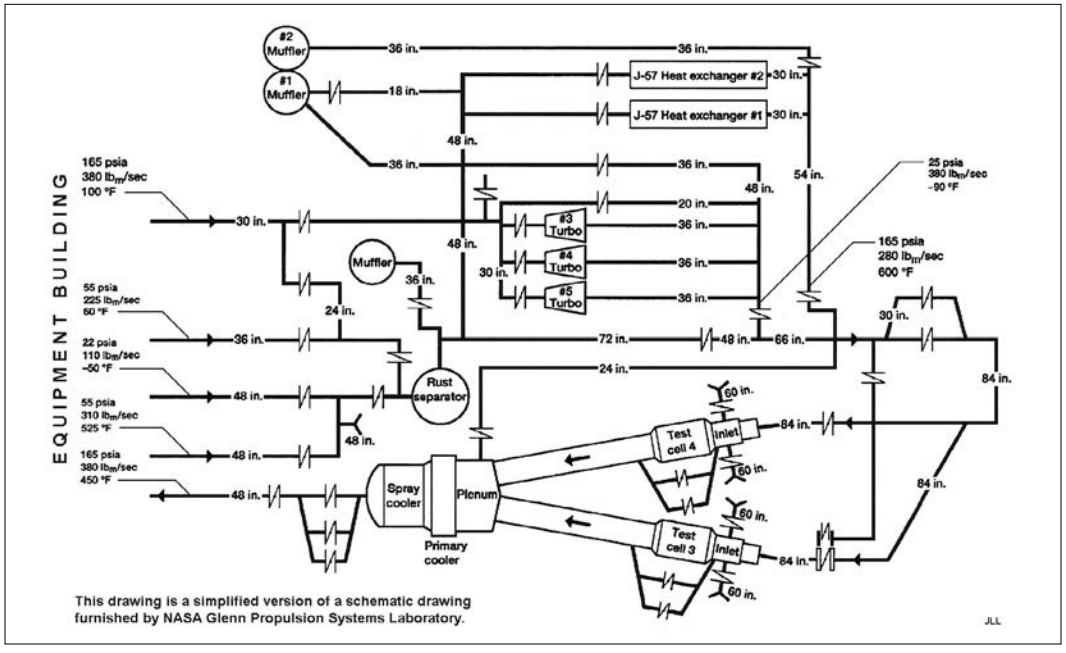


This 1959 photograph shows one of the Elliott compressor sets in the Equipment Building that furnish air to the Propulsion Systems Laboratory's test cells. They are also connected to Glenn's Central Process System. (Photo credit: NASA GRC-1959-C-49575)

The southeast facade of the Engine Test Building in 1969. Test Cells 3 and 4 are located in the high-bay portion of the building. (Photo credit: NASA GRC-1969-C-00721)

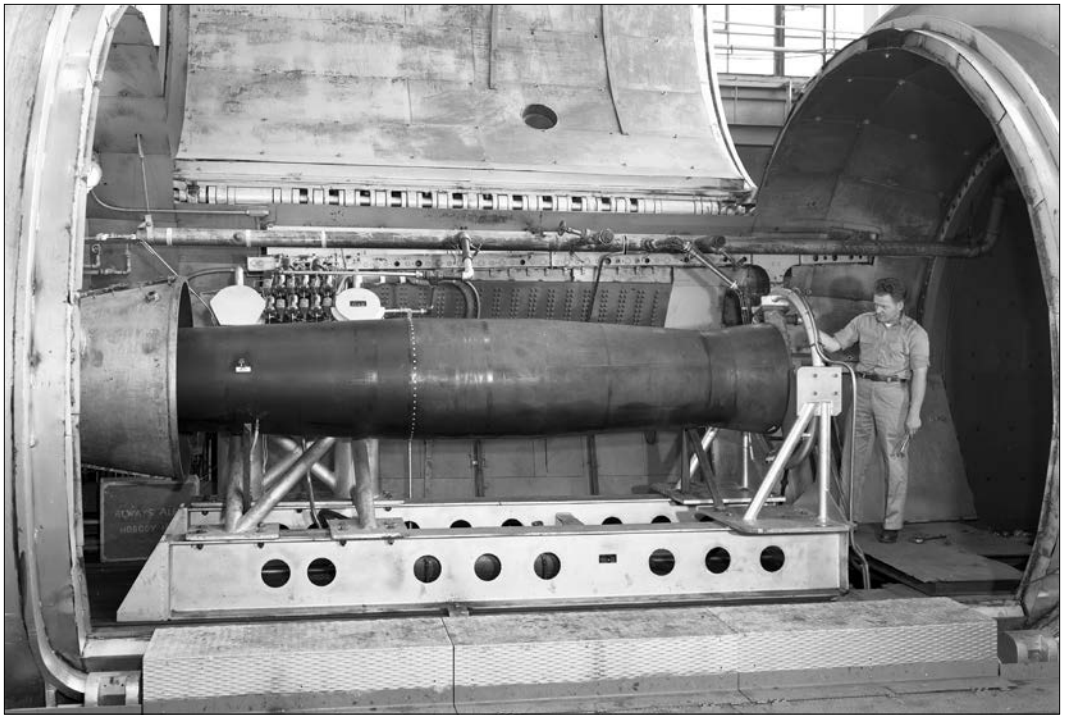


Ormond thrust stands are used to measure engine thrust up to 50,000 pounds. An adapter designed specifically for each engine secures it to the top of the thrust stand. (Photo credit: NASA GRC-1973-C-00704)

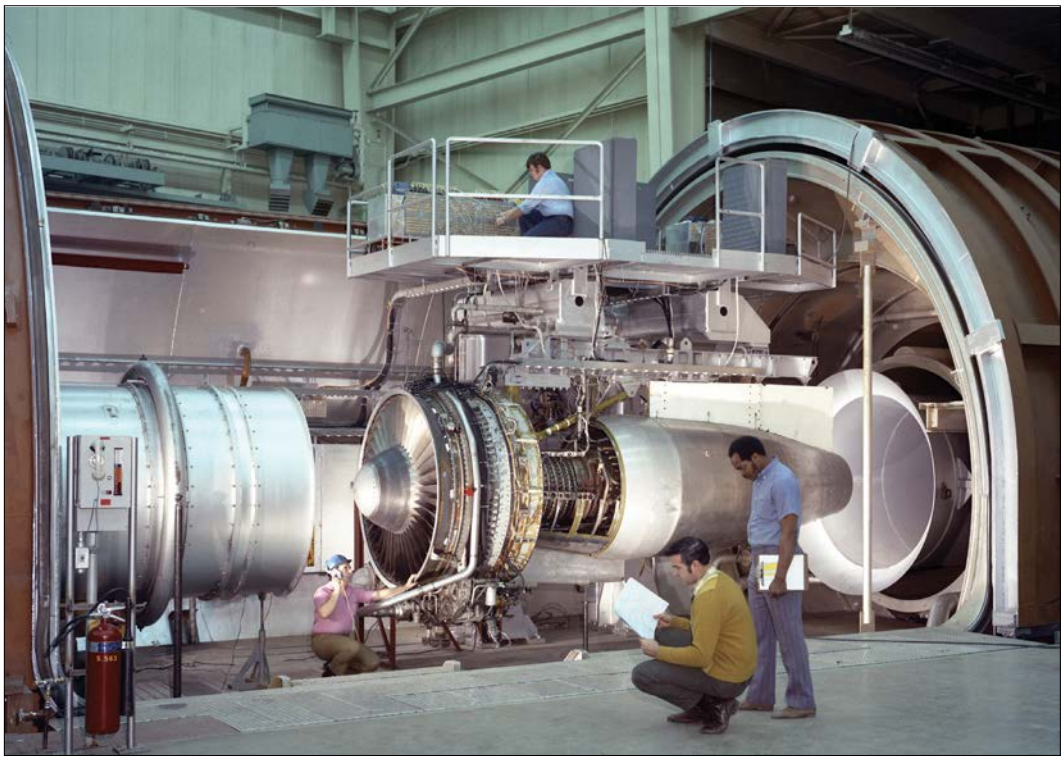


A complex arrangement of equipment, ducts, and valves is needed to deliver the various conditions of test air to Test Cells 3 and 4. Multiple routings of air are possible. The five air supply and exhaust ducts at left go to the equipment building. Only one test cell can operate at a time. A davit valve in the plenum isolates the test cell not being run. (Image credit: J. Lawrence Lee)

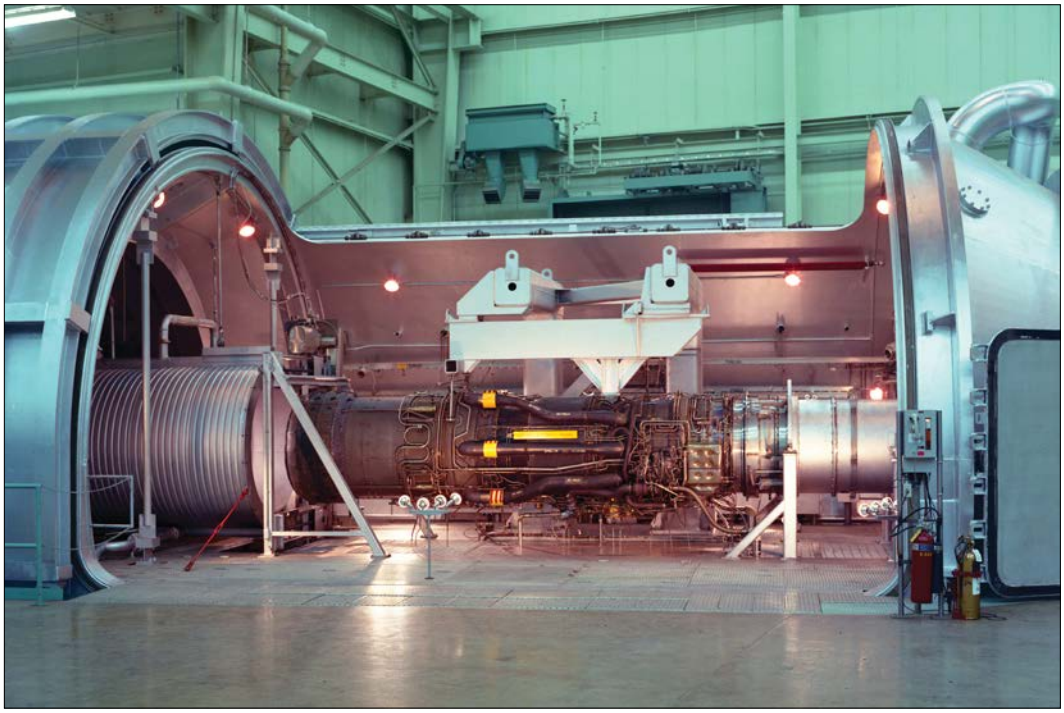
The control room, seen here in 1998, manages all aspects of the test cell and engine during a test. A room housing the data acquisition and preparation hardware is adjacent to the control room. (Photo credit: NASA GRC-1998-C-00729)



This 1955 view of Test Cell 1 shows it with a Marquardt RJ43-MA ramjet engine for a BOMARC anti-aircraft missile installed. The doors for Test Cells 1 and 2 were hinged so that each opened away from the central workspace. (Photo credit: NASA GRC-1955-C-37800)



A prototype quiet turbofan engine installed in Test Cell 3 in 1973. The curved door in the background will rotate over the top to close and seal the chamber for the test run. (Photo credit: NASA GRC-1973-C-00705)



Test Cell 4 with a Pratt & Whitney J58 engine installed for testing in 1973. The J58 was a hybrid turbojet/fan-assisted ramjet that powered the SR-71 Blackbird to speeds above Mach 3. (Photo credit: NASA GRC-1973-C-04113)

42-INCH HYPERSONIC TUNNEL FACILITY

The Hypersonic Tunnel Facility is seen here in 2006. (Photo credit: NASA GRC-2006-C-01719)

SIGNIFICANCE

The 42-Inch Hypersonic Tunnel Facility (HTF), also known as the Hypersonic Test Facility, at the Armstrong Test Facility (formerly Plum Brook Station) is America's largest free-jet hypersonic wind tunnel using non-vitiated air as its test gas. Modifications to key systems were made in 2000 to support direct-connect test capabilities, which allowed the HTF to perform tests on isolated full-scale combustion chambers and fuel injection methods, and to develop hypersonic air-breathing propulsion testing diagnostic instrumentation.[107]

DESCRIPTION

The HTF is a free-jet, blowdown tunnel with an open test section housed within a sealed test chamber. The facility uses a synthetic air system operating up to 1,200 psi, heated up to 3,540°F, as the primary test medium presented to the test article. A diffuser incorporating a water-spray cooler and a large single-stage steam ejector provides altitude simulation from sea level up to 120,000 feet inside the facility test chamber. Three interchangeable nozzles deliver test speeds of Mach 5, 6, and 7. Test runs can extend to 4 minutes, depending on the particular Mach nozzle and the design of the test article. The HTF is unique in that all consumables (gases, water, stored heat) can be recovered daily. This allows the HTF to conduct a blowdown operation each day for test customers.[108]

Externally, the HTF appears as a rectangular, corrugated metal building with a domed cylinder next to its east end and a long, horizontal duct extending 150 feet beyond the cylinder. The steel-framed, metal building has a single concrete floor. The

north half of the structure houses the facility's electrical gear, auxiliary equipment, and a small office; the south portion was built with a high-bay area for the shop and a portion of the tunnel known as the "hot train." Two rows of industrial windows and translucent corrugated fiberglass blowout panels admit ambient light to the shop and hot train areas. A four-floor chamber below the eastern high-bay area provides space for the tunnel's graphite storage heater, a 40-foot-high cylindrical pressure vessel that raises the temperature of the HTF's inlet nitrogen gas to prevent its liquefaction leaving the nozzle. The portion of the main floor over this chamber is composed of removable checker-plate steel panels with an opening for the top of the heater. The hot train tees off it at a right angle and runs eastward to penetrate the test chamber wall. A vent stack, extending ~80 feet above grade directly above the heater, was part of the facility's original configuration in the 1960s. This stack has never been used by the HTF in its tunnel configuration.

In operation, the HTF's synthetic air flow begins as gaseous nitrogen that is stored in a 663,500-cubic-foot railroad tank car at up to 4,500 psi. The tank car does not move, and it is recharged from local supplies as needed. Nitrogen from the tank car passes a regulator that lowers its pressure to 1,200 psi and continues to the graphite storage heater, where it flows around the core and then vertically up through 1,100 holes drilled in the susceptor blocks. The preheated core heats the nitrogen to temperatures approaching 4,100°F.

Leaving a tee mounted on top of the graphite storage heater, the first element of the tunnel's 18-inch-diameter hot train, the hot nitrogen gas flows past the radiation shutter valve (RSV), which is in its "open" state. Immediately downstream of the RSV is a diluent gas injection flange that admits controlled amounts of oxygen and, as necessary, additional cold nitrogen to create a test gas equivalent to the composition of atmospheric air while maintaining a constant stagnation temperature of the test gas. The on-condition run time is determined by the ability of the control valves to maintain this composition and temperature.[109]

Immediately downstream are injectors that admit controlled amounts of oxygen and, if necessary, additional nitrogen to make the test gas roughly equivalent to the composition of atmospheric air. A specific diluent gas injection flange is used for each Mach number to optimize mixing. On-condition stagnation temperatures for free-jet operations are in the range of 1,500 to 3,000°F. Direct-connect operations are at lower temperature ranges. All components of the hot train are aggressively water-cooled with demineralized water at elevated pressures.[110] The synthetic air then expands through the selected nozzle, and a 42-inch-diameter jet blows across the open test section and past the model, where a water-cooled diffuser with a flared inlet directs it into an exhaust diffuser. When operating in direct-connect mode, all of the synthetic airstream issuing out of the hot train passes through the test article, typically a combustion chamber.

The test section is enclosed by a 25-foot-diameter, 20-foot-high steel test chamber with a domed top and external bracing designed to withstand internal pressures as

low as 0.1 psia. The nozzle extends 8 feet, 9 inches into the test chamber and measures 3 feet, 6 inches in diameter at its opening. The 4-foot, 7-inch-diameter diffuser also extends into the test chamber, but it is longitudinally adjustable so that the length of the open test section can be set from 4 feet, 3 inches to 9 feet, 10 inches. Most models are mounted on an injection system that is suspended on rails over the test section. The device translates longitudinally and is equipped to insert and remove models from the airstream during tunnel starts and stops.

Leaving the test chamber through the diffuser, the exhausting gas passes a water-spray cooler that increases its density and through the throat of the steam ejector that maintains the test chamber's low pressure. The gas and steam exit to atmosphere 80 feet from the steam-injection point.

The storage heater consists of 15 stacked graphite blocks, each 6 feet in diameter and 2 feet high. Each has 1,100 axial holes and hexagonal keys to keep these holes aligned inside the heater vessel. The core is surrounded by graphite insulation and a helical coil of 1.625-inch copper tubing that functions as an electric inductance coil. When energized with a 3-megawatt, 750-volt, 180-Hertz single-phase current, the resulting magnetic field induces a secondary current in the outer part of the graphite. Since the graphite has a high resistance, it heats up, and heat is transferred conductively to the remainder of the core. The heating process must be slow and carefully controlled to prevent cracking, and it can take up to 100 hours to heat the core to its 4,500°F maximum temperature. All of this is contained within a 40-foot-high, 9-foot, 2-inch-diameter steel pressure vessel with a 4-inch-thick wall designed to operate at 1,200 psi. Only inert nitrogen gas flows through the heater to prevent deterioration of the graphite that would occur with oxygen exposure at high temperature. Accordingly, oxygen is added in the hot train to approximate the composition of atmospheric air at the selected altitude.

A large single-stage ejector, requiring roughly 560 pound mass per second of steam to operate, provides the downstream suction required to initiate and sustain the hypersonic free jet in the test chamber. This flow rate of steam is provided by five accumulators containing superheated water "charged" to 500 psi by a remotely located boiler house. A full charge on the accumulators can provide 5 minutes of ejector operation. The accumulators can be recharged, ready to support a test run, in 12 hours.[111]

The HTF's cooling system uses demineralized water at 400 psi in a closed loop to cool the hot train and, if necessary, the model or other test hardware. This system also circulates water through the storage heater induction coils to cool them. A heat exchanger transfers this heat to a secondary water loop that circulates through an atmospheric cooling tower. A third system delivers demineralized water to the mixer and diffuser spray at 120 psi. A reverse-osmosis demineralizer supplies the demineralized water, which is stored in three 6,500-gallon tanks.

Gaseous hydrogen used to power test engines was originally stored in an 800-gallon high-pressure liquid hydrogen dewar that was designed to support the facility. It was initially pressed into service as a high-pressure water storage vessel for the HTF but was

removed from supporting any phase of the HTF operation in the 1990s. An electrically heated pebble-bed heater was initially available to heat 150 pounds per minute to 1,200°F for up to 90 seconds. This element was not used after 1990 and was subsequently removed.

With the high energies involved in tests at the HTF, its reinforced concrete control room is located in the Control and Instrument Building approximately 1,400 feet away. The building has also contained control rooms for other test facilities. HTF was originally operated through a main panel using hard-wired circuits, but a 2000 modernization project replaced most of this with programmable logic controllers and computerized test control and data acquisition equipment.

HISTORY

The HTF was originally constructed as the Hydrogen Heat Transfer Facility (HHTF) to conduct high-temperature heat transfer studies to support the nation's nuclear rocket program. Its central element was a 3-megawatt graphite storage heater system. Gaseous nitrogen was processed at high pressure through the storage heater and presented to a rocket nozzle being cooled by liquid hydrogen.[112] A tall stack exhausted the hydrogen gas to atmosphere safely above the facility. The HHTF was completed in 1967 but did not contribute to any research programs.

In 1968, the Langley-based Hypersonic Research Engine (HRE) Program had progressed to the point of building a prototype engine, but no existing facility could test it. The HHTF graphite storage heater was capable of providing nitrogen gas flows at stagnation temperatures required to simulate hypersonic flight conditions, and the HHTF building was designed to handle hydrogen gas. Repurposing the HHTF into a hypersonic air-breathing propulsion ground test facility was the most cost-effective pathway to testing the prototype. Engineers designed a tee connection for the top of the heater and a horizontal, blowdown tunnel with an open-jet test section in a sealed test chamber as well as a diffuser containing a spray cooler and a steam ejector. They designed three interchangeable nozzles for Mach numbers of 5, 6, and 7, as well as the cooling-water and control systems. At the time, Lewis and Plum Brook personnel associated with the nuclear rocket program expected the HTF conversion to be temporary, and that it would be changed back to its HHTF configuration for tests of nuclear nozzles using hot hydrogen. Cancellation of the nuclear program in early 1973 precluded any such change.[113]

The facility, renamed the HTF, was essentially completed in 1969, but start-up problems abounded, particularly with the pebble-bed heater. The pebble bed was replaced with a susceptor core made up of graphite blocks surrounded by carbon-fiber insulation. By this time, the elaborate model support and thrust stand were installed. Additional problems delayed the HTF's calibration runs until July 1971. These were successfully completed, and testing of the Garrett AiResearch-built HRE occurred during 1972–74.[114]

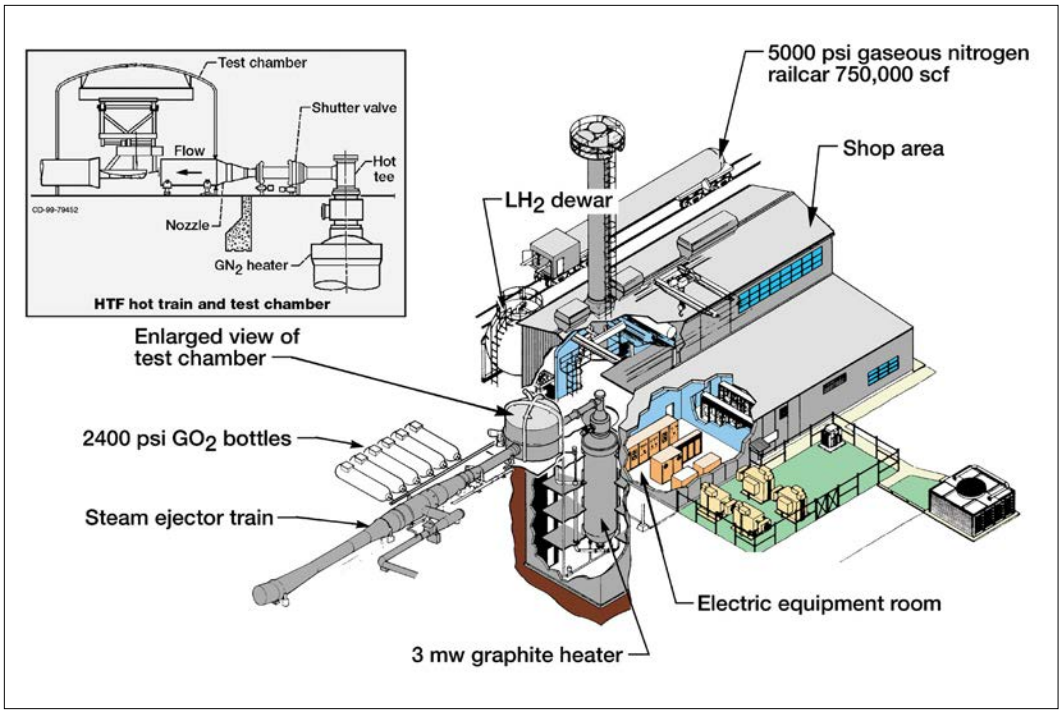
Hypersonic research has repeatedly endured boom-and-bust cycles depending on the political support of the time. The HTF had no tests booked after the completion of the HRE test program, so management decided to put it in "mothball" status. Technicians

prepared it for long-term storage in place, and it remained mothballed until 1990, when a renovation project to reopen the HTF began. Over a three-year period, all of its fluid systems were inspected, repaired, and recertified, and both the graphite heater and the control systems were refurbished. Testing of the facility began in 1994, and the renovated HTF saw its first scramjet test in July 1996. Unlike the HRE, these engines were integrated into the fuselage, and much of the work done in the HTF involved inlet design. As had been the case during the 1970s, problems were experienced with erosion of the graphite susceptor blocks. The erosion resulted from water leaking from the induction coils. Seals were renewed, and operating changes were instituted to minimize water intrusion. Operations went smoothly until the RSV failed during a Mach 7 run in September 1996. High-pressure nitrogen at 4,000°F breached the cooling channels, resulting in much of the RSV and its actuator melting and flying apart. With the loss of cooling water, all of the hot train sustained serious damage, as did the heater's susceptor blocks and induction coil.[115]

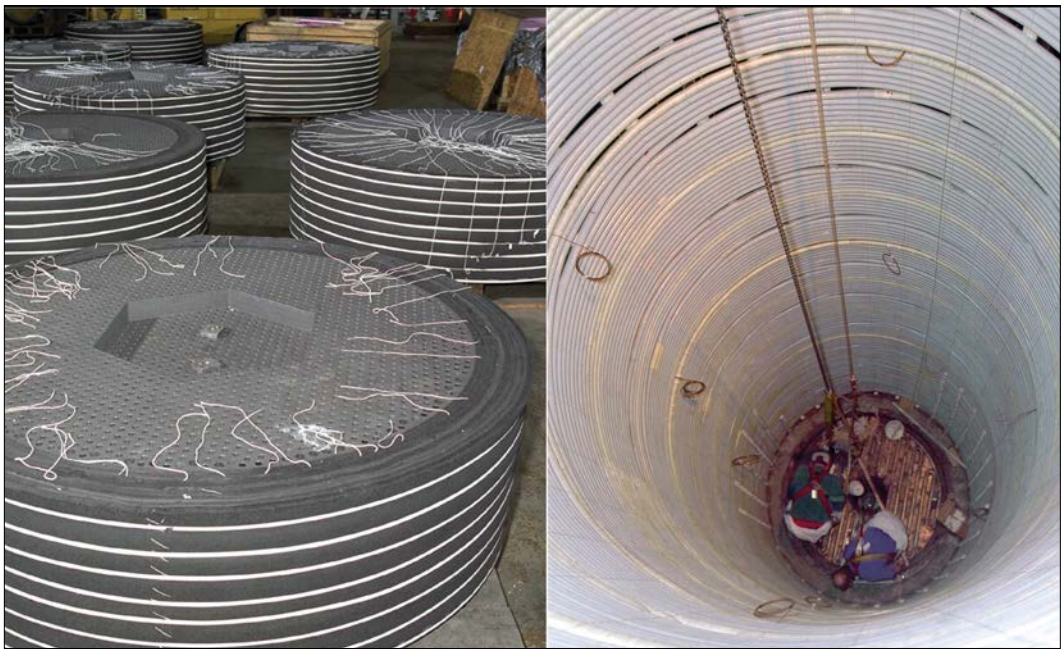
NASA decided to rebuild the HTF once again in 1997, but this project involved a lot of new equipment and improved processes to maximize reliability. Operating procedures were also reviewed and modified to improve safety and implement the new computerized control system, which included new sensors to monitor the critical equipment. Engineers evaluated the RSV design to determine the reason for its failure and built a new RSV with modifications to reduce stress in key areas and improve seal performance. This rebuilding, completed in 2000, resulted in the restoration of the HTF's full capabilities, as well as enhanced reliability.[116]

Following the second rebuild of the HTF, a series of modifications were made to the synthetic air system, as well as the fabrication of special test equipment, which enabled the HTF to be configurable for either free-jet or direct-connect flow path. For direct-connect testing, the entire hot train flow passed through test article, typically an engine combustion chamber.[117] This arrangement allowed researchers to study the difficult issues involved with hypersonic ignition and combustion without the tests being affected by other engine or airframe components. An interchangeable "dummy" section replaced the actual combustor section for tunnel calibration. Both sections were mounted on carts that made it easy for technicians to swap them without having to use an overhead crane or separate jacks.[118]

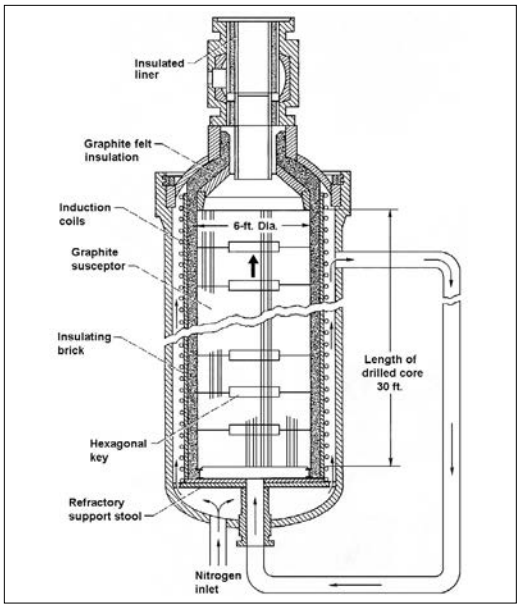
As part of the Integrated System Test of an Airbreathing Rocket (ISTAR) Project, a series of Rocket-Based Combined-Cycle (RBCC) propulsion tests in the HTF yielded a considerable quantity of useful data, but interest in the proposed X-30 National Aero-Space Plane (NASP) that might use such a propulsion system waned, and the NASP program was canceled in 1993. A resurgent interest in hypersonic air-breathing propulsion in the late 1990s led to the rebuild of the HTF after the RSV failure. By 2000, the national interest had waned again with the exception of the Dual Combustion Ramjet test program. The facility was converted and a test article built, but the program was canceled before any testing occurred. In 2006, the HTF was placed in a deep standby status.[119]



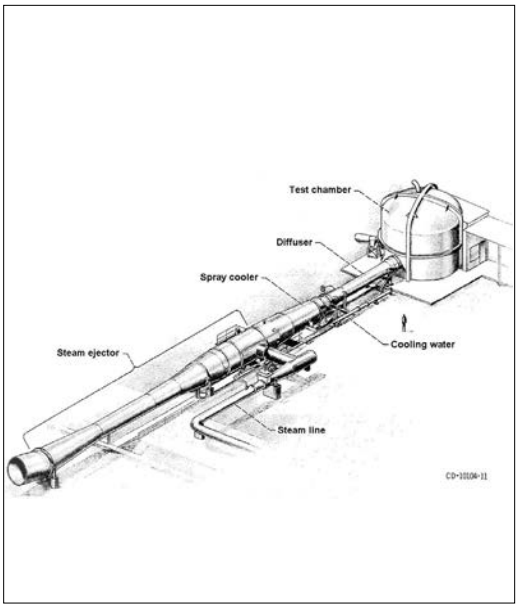
This plan drawing of the Hypersonic Tunnel Facility shows its overall arrangement and major components. (Image credit: NASA CD-99-79449)



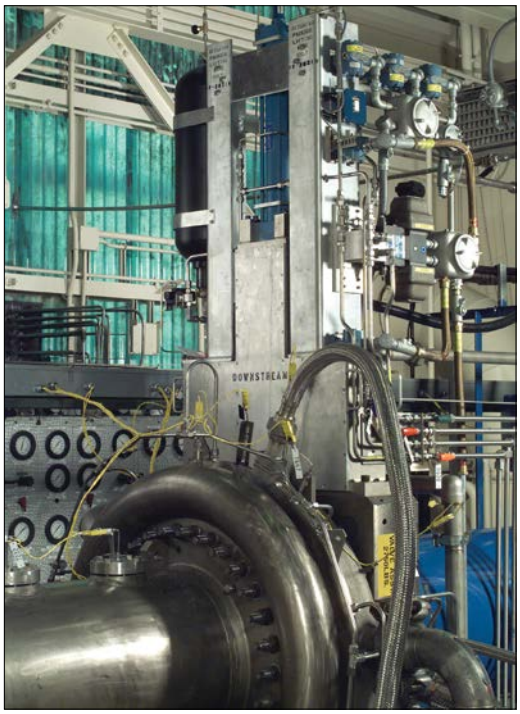
The image on the left shows the wrapped susceptor blocks prior to installation into the Hypersonic Tunnel Facility. On the right, technicians work at the bottom of the heater, which is lined by the electric coils. (Photo credit: NASA HTF-C-1)



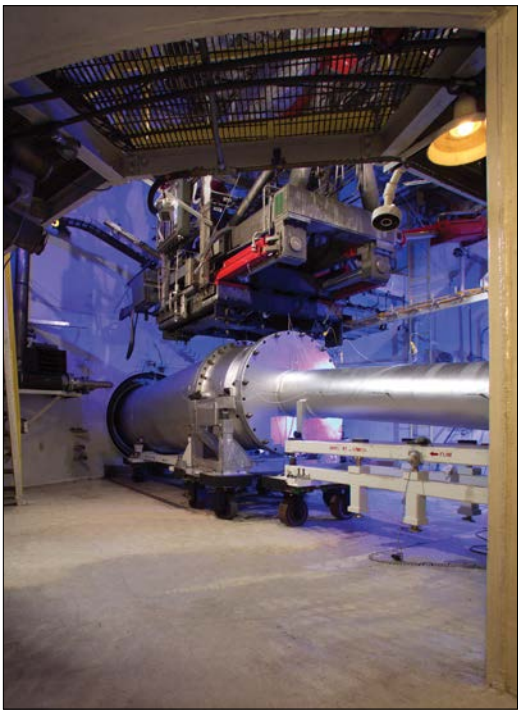
The storage heater uses electric coils to inductively heat the graphite susceptor to 4,500°F. Nitrogen gas passes through the holes and absorbs this heat during test runs. All of the storage heater except the top outlet is located below grade level. (Image credit: NASA TM-2000-209930, Fig. 4)



A 150-foot-long diffuser, cooler, and steam ejector assembly exhausts the Hypersonic Tunnel Facility's test gas while simulating altitudes as high as 120,000 feet in the test chamber. (Image credit: NASA CD-10104-11)

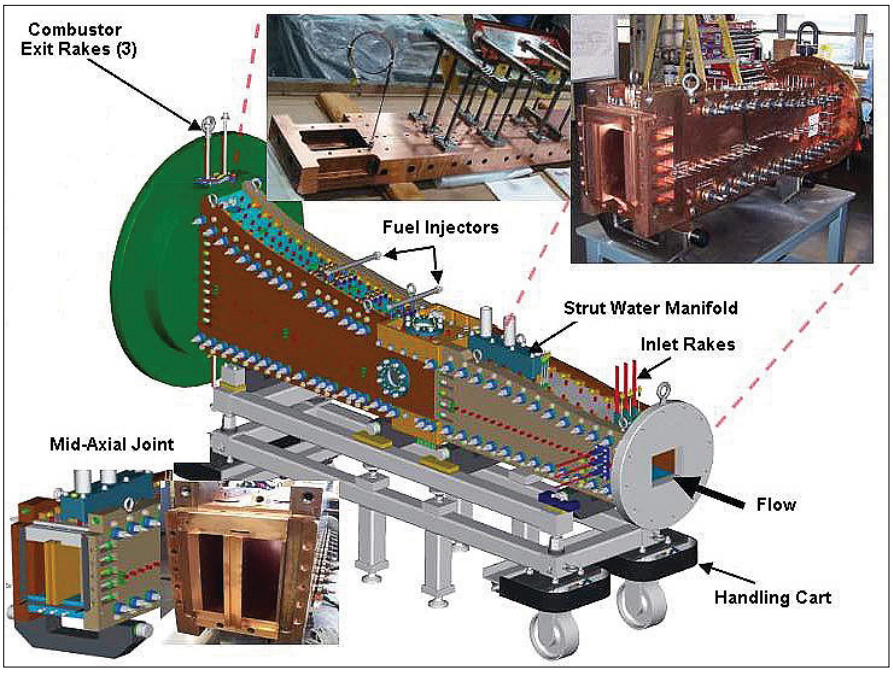


An enlarged view of the radiation shutter valve, the Hypersonic Tunnel Facility's main flow control. The term "radiation" refers to infrared (heat) radiation. (Photo credit: NASA GRC-2000-C-00111)

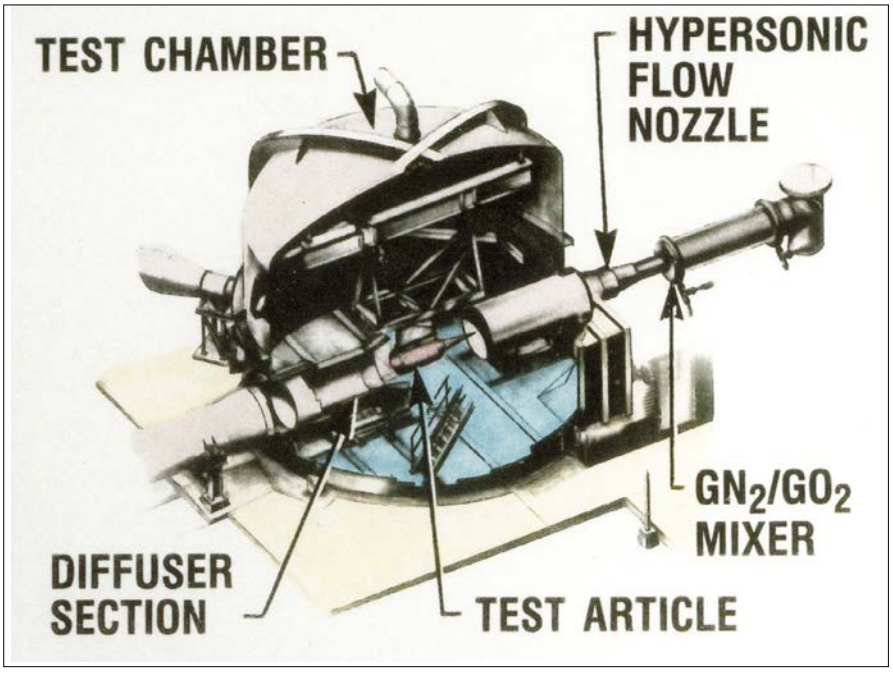


The Direct Connect Combustion Rig, used for rocket-based-combined-cycle development testing, converted the Hypersonic Tunnel Facility test section from an open-jet to a closed configuration that simulates only an engine's combustion chamber. The smaller-diameter pipe shown here in 2004 is a dummy insert used for calibration. The model support and injection system used with open-jet testing is clearly visible over the tunnel. (Photo credit: NASA GRC-2004-C-01718)

Engineers inspect the inlet of a prototype Hypersonic Research Engine scramjet prior to a test run in the Hypersonic Tunnel Facility. (Photo credit: NASA GRC-1973-C-02625)



The primary elements of the Direct Connect Combustor Rig are detailed here. This assembly replaced the dummy insert in the Hypersonic Tunnel Facility, and it allowed researchers to study hypersonic ignition and combustion problems apart from any effects introduced by the remainder of the engine or airframe. (Image credit: NASA/TM—2005-213432, Fig. 7)



This cutaway drawing shows the arrangement (relative to the hot tee) of the test chamber, the Mach nozzle in the chamber, the model and model support structure, and the water-cooled diffuser, which together compose the free-jet test environment. (Image credit: NASA CD-93-63760)

ENDNOTES

1 For a comprehensive history of the pre-Glenn Lewis Center, see Virginia P. Dawson, *Engines and Innovation: Lewis Laboratory and American Propulsion Technology* (Washington, DC: NASA SP-4306, 1991) and Robert S. Arrighi, *Bringing the Future Within Reach—Celebrating 75 Years of the NASA John H. Glenn Research Center* (Washington, DC: NASA SP-2016-627, 2016).

2 Except as noted, description and performance data were compiled from Robert S. Arrighi, "Historic American Engineering Record Documentation of the NASA Altitude Wind Tunnel and Space Power Chambers" (Cleveland, OH: NASA GRC, 2009), pp. 1–9; "Altitude Wind Tunnel at NASA Glenn Research Center: An Interactive History," *Special Publication 2008-4608*, electronic media (Cleveland, OH: NASA GRC, 2008); and "Altitude Wind Tunnel," *Major Research Facilities of the Lewis Flight Propulsion Laboratory* (Cleveland, OH: NACA Lewis Flight Propulsion Laboratory, 31 Aug. 1956), Test Facilities Collection, NASA Glenn Research Center History Office. See also Virginia P. Dawson, *Engines and Innovation: Lewis Laboratory and American Propulsion Technology* (Washington, DC: NASA, 1991), pp. 27–30; and Ernest G. Whitney, "Altitude Wind Tunnel at AERL," 23 June 1943 lecture, Director's Collection, Boxes 1B1/1B2 F.764, NASA Glenn Research Center History Office.

3 This was the maximum speed at a simulated altitude of 30,000 feet. At sea level, the denser air reduced the tunnel's top speed to 250 miles per hour. Some sources have reported maximum speeds as high as 500 miles per hour, but higher speeds may have been predicated on higher altitudes.

4 Dawson, *Engines and Innovation*, pp. 8–10, 27, 242. Also Robert S. Arrighi, *Revolutionary Atmosphere: The Story of the Altitude Wind Tunnel and the Space Power Chambers* (Washington, DC: NASA SP-4319-2010, 2010) pp. 12–15.

5 Arrighi, *Revolutionary Atmosphere*, pp. 22–24. Also *Dawson, Engines and Innovation*, pp. 19–21, 27. Also Walter Vincenti, conversation with author, 18 Aug. 2007.

6 "Log of Altitude Wind Tunnel Investigations," File 2E1, Box 5, NASA Glenn Research Center History Office.

7 "Information on Altitude Wind Tunnel," typed description of the AWT dated 10 Sept. 1953, p. 3, Director's Collection, NASA Glenn Research Center History Office.

8 Some sources incorrectly refer to this phenomenon, the varying diffusion of electromagnetic radiation passing through a medium based on wavelength, as "rally scattering," but it was named for Lord Rayleigh, the British physicist who first described it. For a thorough discussion of Rayleigh scattering, see C. F. Bohren and D. Huffman, *Absorption and Scattering of Light by Small Particles* (New York: John Wiley, 1983).

9 For the Duct lab, see "Altitude Wind Tunnel at NASA Glenn Research Center: An Interactive History," *Special Publication 2008-4608*. The IRT and the supersonic tunnels, collectively known as the Small Supersonic Tunnels, are discussed in their own chapters.

10 "Altitude Wind Tunnel at NASA Glenn Research Center: An Interactive History," *Special Publication 2008-4608*.

11 Loyd S. Swenson, Jr., James M. Grimwood, and Charles C. Alexander, *This New Ocean: A History of Project Mercury* (Washington, DC: NASA SP-4201, 1998) pp. 244–245.

12 "AWT Gets New Assignment," *Orbit* XX, no. 1 (Cleveland, OH: NASA Lewis Research Center, 12 Jan. 1962): 1. Also "Lewis Research Center Facilities Bldg. 7" (Cleveland, OH: NASA Lewis Research Center, 1975). Also Memorandum For Those Concerned from Abe Silverstein, Director, "Updating of Name of Structure Number 7 of the Lewis Research Center," 12 Sept. 1962, Director's Collection, NASA Glenn Research Center History Office.

13 "Altitude Wind Tunnel (AWT) Rehabilitation: Report of the Major Aeronautical Facility Requirements Subpanel to the Aeronautics Panel, Aeronautics and Astronautics Coordinating Board," Nov. 1981, Test Facilities Collection, Glenn Research Center History Office.

14 Arrighi, *Revolutionary Atmosphere*.

15 "Altitude Wind Tunnel," Glenn Research Center, *http://www1.grc.nasa.gov/historic-facilities/altitude-wind-tunnel/*.

16 Descriptive and performance data were compiled from *Icing Research Tunnel: An International Historic Mechanical Engineering Landmark* (New York: ASME, 1987); "Lewis Research Center Facilities," Bldg. 11; and "Icing Research Wind Tunnel," *Major Research Facilities of the Lewis Flight Propulsion Laboratory,* Test Facilities Collection, NASA Glenn Research Center History Office.

17 For modernization, see William M. Leary, *"We Freeze to Please": A History of NASA's Icing Research Tunnel and the Quest for Flight Safety* (Washington, DC: NASA SP-4226-2002, 2002), pp. 99–101.

18 Ibid., pp. 32–33. Also Donald R. Mulholland and Porter J. Perkins, "Investigation of Effectiveness of Air-Heating a Hollow Steel Propeller for Protection Against Icing, I–Unpartitioned Blades," *Technical Note 1586* (Washington, DC: NASA, 1948), p. 3.

19 For original performance, see note 1. For current performance, see "Icing Research Tunnel," NASA Glenn Research Center, *https://www1.grc.nasa.gov/facilities/irt/* (accessed 29 March 2024).

20 Freon is a trademark of E. I. DuPont deNemours and Company.

21 Leary, *"We Freeze to Please,"* pp. 27, 175–177. Also see the Altitude Wind Tunnel section of this book.

22 Christine Pastor-Barsi, Allen Arrington, and Judith VanZante, "Aero-Thermal Calibration of the NASA Glenn Icing Research Tunnel (2012 Test)," Aero-Thermal Calibration of the NASA Glenn Icing Research Tunnel (2012 Test)," 47th Atmospheric and Space Environments Conference, 26 June 2012.

23 See the Langley Low-Turbulence Tunnel section of this book for further information.

24 For a more detailed discussion of early icing research, see Leary, *"We Freeze to Please,"* pp. 1–18.

25 Ibid., pp. 19–20. Also Dawson, *Engines and Innovation,* p. 110.

26 Ibid., pp. 19–22.

27 "Report of Accident in Icing Research Tunnel, December 29, 1944," 5 typed pages, Test Facilities Collection, NASA Glenn Research Center History Office.

28 Leary used the phrase "a golden age" as the title of chapter 3 of his history of the IRT entitled, *"We Freeze to Please."* The NACA published over 100 test reports of icing studies during this period, many of which were summarized in Uwe von Glahn, "The Icing Problem—The Current Status of NACA Techniques and Research," a 1955 paper reproduced in "Select Bibliography of NACA-NASA Aircraft Icing Publications, *Technical Memorandum 81651* (Washington, DC: NASA, 1981), pp. 1–10.

29 Michael D. Mastaler, NASA Aeronautics Test Program Headquarters Liaison, to author, 23 Jan. 2010.

30 The "3-Square Foot" term that appears on one rendering is curious for several reasons, especially without a second hyphen. None of these tunnels had a cross sectional area of either 1 or 3 square feet, and the rendering shows that one of them was circular. This term saw little, if any, other use.

31 Description and performance data for these tunnels were compiled from "Small Supersonic Tunnels," *Major Research Facilities of the Lewis Flight Propulsion Laboratory*, 31 Aug. 1956, Test Facilities Collection, NASA Glenn Research Center History Office; data listed on NACA photograph C-1946-14156; and Carlton Kemper to NACA, "Outline of Research Projects for the 18- by 18-Inch and 20-Inch Supersonic Tunnels at the Cleveland Laboratory," 4 Oct. 1946, Director's Collection, NASA Glenn Research Center History Office.

32 *Dawson, Engines and Innovation*, pp. 73–74.

33 Documents referring to this project are rare, implying that it was one of the NACA's many "bootleg" projects, accomplished by local scavenging, funds made available by other projects, and in-house labor. Consequently, historic photographs in the Glenn Archives furnish some of the best evidence concerning the history of this group of tunnels. For the rendering, see NACA photograph C-1946-14156.

34 For the conflicting dates, see "Small Supersonic Tunnels," p. 2; Dawson, *Engines and Innovation*, p. 73; and NACA photographs C-1945-15053 and C-1946-15686. Also see Kemper to NACA, 4 Oct. 1946. Also Robert Arrighi, NASA Glenn Archivist, to author, 1 Dec. 2009.

35 "Small Supersonic Tunnels," p. 2.

36 Kemper to NACA, 4 Oct. 1946.

37 See NACA photograph C-1946-14156.

38 Two SST test programs for which reports were published are H. Fred Goelzer and Edgar M. Cortright, Jr., "Investigation at Mach Number 1.88 of a Conical Spike Diffuser Mounted as a Side Inlet with Boundary-Layer Control," *Research Memorandum E51G06* (Washington, DC: NACA, 1951); and Edgar M. Cortright, Jr., "Preliminary Investigation of a Translating Cowl Technique for Improving Take-Off Performance of a Sharp-Lip Supersonic Diffuser," *Research Memorandum E51I24* (Washington, DC: NACA, 1951). Both *RMs* dealt with jet engine inlets, a topic that also involved hundreds of hours of testing time in the 8- by 6-Foot Supersonic Tunnel.

39 "NASA Lewis Research Center Facilities" (Cleveland, OH: NASA Lewis Research Center, 1975), Bldg. 33.

40 Descriptive and performance information was compiled from "8- by 6-Foot Supersonic Wind Tunnel," *Major Research Facilities of the Lewis Flight Propulsion Laboratory,* 1956, Director's Files, NASA Glenn Research Center History Office; Robert J. Swallow and Robert A. Aiello, "NASA Lewis 8- by 6-Foot Supersonic Wind Tunnel," *Technical Memorandum X-715421* (Washington, DC: NASA, 1974); Ronald H. Soeder, "NASA Lewis 8- by 6-Foot Supersonic Wind Tunnel User Manual," *Technical Memorandum 105771* (Washington, DC: NASA, 1993), pp. 1–14; Joseph A. Yushka, James H. Diedrich, and Nestor Clough, "Lewis 8- by 15-Foot V/STOL Wind Tunnel," *Technical Memorandum X-2305* (Washington, DC: NASA, 1971); Ronald H. Soeder, "NASA Lewis 9- by 15-Foot Low-Speed Wind Tunnel User Manual," *Technical Memorandum 106247* (Washington, DC: NASA, 1993), pp. 1–32; and 8- by 6-Foot *Supersonic Wind Tunnel/9- by 15-Foot Low-Speed Wind Tunnel Complex: 50 Years of Testing, 1949–1999* (Cleveland, OH: NASA GRC, 1999).

41 Stephanie Simerly comment from Taylor Varouh to Robert Arrighi, "RE: 8×6 / 9×15 History Review," 29 January 2023.

42 Ibid.

43 Ibid.

44 Ibid.

45 Ibid.

46 Ibid.

47 Ibid.

48 Ibid.

49 See the Glenn Small Supersonic Tunnels section of this book for further information.

50 *8- by 6-Foot Supersonic Wind Tunnel/9- by 15-Foot Low-Speed Wind Tunnel Complex,* pp. 1–2.

51 Ibid., pp. 2–5.

52 One secondary source for the quotation is Donald D. Baals and William R. Corliss, *Wind Tunnels of NASA* (Washington, DC: NASA, 1981), p. 53. For a sense of the engineering challenge, see two Memoranda for Record, "Visit of Mr. Sam Labate, Bolt and Baranek, Acoustic Consultants," 16 Sept. 1949, and 12 October 1949, Test Facilities Collection, NASA Glenn Research Center History Office.

53 *8- by 6-Foot Supersonic Wind Tunnel/9- by 15-Foot Low-Speed Wind Tunnel Complex,* pp. 8–9.

54 Ibid., pp. 8–10.

55 Ibid., p. 1. Also Joseph A. Yushka, James H. Diedrich, and Nestor Clough, "Lewis 9- by 15-Foot V/STOL Wind Tunnel," *Technical Memorandum X-2305* (Washington, DC: NASA, 1971), pp. 1–2, 12–19, 20–26.

56 Stephanie Simerly comment from Taylor Varouh to Robert Arrighi, "RE: 8×6 / 9×15 History Review," 29 January 2023.

57 *8- by 6-Foot Supersonic Wind Tunnel/9- by 15-Foot Low-Speed Wind Tunnel Complex,* pp. 18, 20. Reports of typical test programs include James H. Dittmar and David B. Strang, "Cruise Noise of the 2/9th Scale Model of the Large-Scale Advanced Propfan (LAP)

Propeller, SR-7A," *Technical Memorandum 100175* (Washington, DC: NASA, 1987); G. E. Hoff et al., "Experimental Performance and Acoustic Investigation of Modern Counterrotating Blade Concepts," *Contractor Report 185158* (Washington, DC: NASA, 1990); and Albert L. Johns, George Neiner, Timothy J. Bencic, Joseph D. Flood, Kurt C. Amuedo, and Thomas W. Strock, "Hot Gas Ingestion Test Results of a Two-Poster Vectored Thrust Concept With Flow Visualization in the NASA Lewis 9- by 15-Foot Low Speed Wind Tunnel," *Technical Memorandum 103258* (Washington, DC: NASA, 1990).

58 Descriptive and performance information was compiled from "10- by 10-Foot Unitary Supersonic Wind Tunnel," *Major Research Facilities of the Lewis Flight Propulsion Laboratory,* 1956, NASA Glenn Research Center History Office, Test Facilities Collection; "Manual for Users of the Unitary Plan Wind Tunnel Facilities of the National Advisory Committee for Aeronautics," *Technical Memorandum 80998* (Washington, DC: NACA, 1956), pp. 85–94, 104; and Ronald H. Soeder, James W. Roeder, Alan A. Linne, and Joseph W. Panek, "User Manual for NASA Glenn 10- by 10-Foot Supersonic Wind Tunnel," *Technical Memorandum 2004-212697* (Washington, DC: NASA, 2004), pp. 1–11, 37–42.

59 In any supersonic tunnel, there is one particular contour of a converging-diverging nozzle for any given speed and pressure differential. A flexible wall allows the contour and speed to be adjusted to any value within the tunnel's range.

60 Logan Micham to Robert Arrighi, "10×10 History Review," 13 January 2023.

61 James Roeder to Robert Arrighi, "10×10 History Review," 16 January 2023.

62 "National Program of Transsonic [*sic*] and Supersonic Wind Tunnels," Report of the Special Committee on Supersonic Facilities to the National Advisory Committee on Aeronautics, 24 Jan. 1947, NASA Langley Archives, Milton Ames Collection, box 5.

63 For further discussion of the Unitary Plan's development, see R. D. Launius, T. D. Irvine, and E. A. Arrington, "NACA/NASA and the National Unitary Wind Tunnel Plan, 1945–1965," *Paper A02-14248* (Reston, VA: AIAA, 2002), pp. 1–6. Also Alex Roland, *Model Research: The National Advisory Committee for Aeronautics, 1915–1958* (Washington, DC: NASA SP-4103, 1985), pp. 211–221.

64 Baals and Corliss, *Wind Tunnels of NASA*, pp. 69–70.

65 The only comparable tunnel is the Propulsion Wind Tunnel at the U.S. Air Force's Arnold Engineering Development Center in Tullahoma, Tennessee. Its 240,000-horsepower drive can produce speeds of up to Mach 4.7 in its 16- by 16-foot supersonic test section, but it can only operate in a closed-circuit mode and does not have the makeup and exhaust capabilities of the 10- by 10-Foot SWT. The supersonic circuit was mothballed from approximately 1997 to 2021. Tests during that period were run only in its transonic circuit, which uses a fraction of the available power.

66 *The Lewis Unitary Plan Tunnel*, a booklet distributed at the first NACA Inspection of the tunnel on 22 May 1956, Director's Files, NASA Glenn Research Center History Office, pages not numbered.

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This rare photo of the George C. Marshall Space Flight Center on 15 March 1978 shows the Space Shuttle orbiter Enterprise being towed to the Dynamic Test Stand (not visible in photo) for vibration testing. It has just passed Building 4732, the Aero-Astrodynamics Laboratory, on its right. The tall building in the distance is Marshall's main administrative office building. (Photo credit: NASA MSFC-7887857)

GEORGE C. MARSHALL SPACE FLIGHT CENTER

George C. Marshall in 1946
(Public Domain)

The facility now known as NASA's George C. Marshall Space Flight Center[1] had its origins in a field that had no direct association with aviation, let alone spaceflight. Starting in 1941, the area southwest of Huntsville, Alabama, was first developed as a chemical weapons plant and ordnance assembly arsenal by the United States Army's Chemical Weapons Service and Ordnance Division. The two plants soon became collectively known as Redstone Arsenal, the name referring to the red hue of native soil. The base grew into a major producer of incendiary bombs, chemical artillery shells, and smoke grenades during World War II. With the cessation of hostilities, production at the arsenal stopped, and it was placed in standby status early in 1947. Several buildings were subsequently leased to commercial companies.

The Chemical Weapons Service removed the last of its materiel from Redstone in 1948, but the Ordnance Division soon determined that Redstone would be the location for its new center for rocket research and development, thus providing a permanent home for the German rocket engineers who had been brought to the United States under Project Paperclip. In 1950, this operation became the Army's Guided Missile Development Division (GMDD), led by Wernher von Braun. A reorganization of missile activities resulted in the GMDD being replaced and expanded as the Army Ballistic Missile Agency (ABMA) in 1956. The von Braun team developed several missiles for the Army, including the Redstone, Jupiter, and Jupiter-C. A variant of the Jupiter-C named Juno I launched America's first satellite, Explorer 1, into orbit on 31 January 1958.

When Congress created NASA in 1958, the ABMA was not specified for inclusion. The Army and Air Force were still at odds over which service would control the development and deployment of intermediate- and long-range ballistic missiles. After Secretary of Defense Thomas Gates defined their respective roles, it became apparent that von Braun and his team would have to transfer to the Air Force, which they did not wish to do, or become a part of NASA, which had already begun work toward a crewed orbital flight. President Eisenhower and Congress agreed that the ABMA should become a part of NASA, and a formal transfer of assets occurred on 1 July 1960. The new NASA center was named the George C. Marshall Space Flight Center (MSFC) in honor of former General of the Army and Secretary of State George C. Marshall.

MSFC immediately began contributing to the United States' space program. The Redstone missile became a "launch vehicle," and it launched the first suborbital flights of Project Mercury during 1960–61. After President Kennedy announced the goal of a Moon landing, MSFC was charged with designing the Saturn I and Saturn V launch vehicles that would accomplish the task. Wind tunnels—those inherited from the ABMA and those built new by NASA—contributed to both series of Saturn vehicles, as did massive new rocket and dynamic test stands. MSFC also branched out into nonpropulsion activities, becoming the lead center for development of Skylab, its Apollo Telescope Mount, and, later, the Hubble Space Telescope.

The Space Shuttle Program put MSFC in charge of the propulsion systems, including the solid rocket boosters, main engines, and external tank. Development work on the main engines continued throughout most of the program, and the center led major redesign efforts involving the solid rocket boosters and external tank.

MSFC continues to be a primary NASA center for the development of launch vehicles and propulsion systems. It currently has responsibility for the design, development, testing, and engineering of the Space Launch System (SLS), the new super heavy-lift rocket for the Artemis missions.

7- BY 7-INCH BISONIC WIND TUNNEL

MSFC's Wind Tunnel Building (Building 4732) housed the Bisonic Wind Tunnel and Trisonic Wind Tunnel. The sphere at upper right is the receiver tank for the High Reynolds Number Wind Tunnel. (Photo credit: NASA MSFC-9265094)

SIGNIFICANCE

The 7- by 7-Inch Bisonic Wind Tunnel (BWT) was the second wind tunnel built at the Redstone Arsenal and the first by the United States Army's Guided Missile Development Division (GMDD). It was one of the first tunnels to be capable of both sub- and supersonic speeds, and it served as a pilot for Redstone Arsenal's larger Trisonic Wind Tunnel. The BWT was one of the Redstone facilities transferred to NASA in 1960.

DESCRIPTION

The BWT, also known as the 7-Inch Supersonic Tunnel, was an atmospheric blowdown wind tunnel, meaning that the tunnel drew in atmospheric air that it exhausted to a vacuum reservoir, with the pressure differential driving the airflow. Located in Building 4732, the BWT utilized interchangeable blocks with fixed-contour nozzles and test sections to specific supersonic speeds in the range of Mach 1.5–4.5. The tunnel was fabricated primarily from steel, but the two-dimensional nozzles were machined from brass, and all of them discharged into a 7- by 7-inch test section. Removing the supersonic nozzle and adjusting the second minimum of the BWT's controllable diffuser could produce subsonic speeds between Mach 0.4 and 0.9. The tunnel featured a square cross section from its settling chamber through the diffuser. A circular duct led from the

valve to the vacuum reservoir. Valves at the ends of the settling chamber and diffuser isolated the core portion of the tunnel from the air supply and vacuum systems during nozzle-block changes.[2]

The vacuum reservoir consisted of a bank of six interconnected, cylindrical, steel tanks with semi-elliptical ends mounted horizontally on concrete supports. This 42,000-cubic-foot vacuum reservoir served both the BWT and the newer Trisonic Wind Tunnel (TWT), and it continues to serve the latter tunnel. Rotary vacuum pumps in an adjacent pump house evacuated the tanks to 0.019 psia prior to a test run. This permitted run times of up to approximately 180 seconds in the BWT. Multiple runs of shorter duration could be made before a re-evacuation was required.

The atmospheric air for the BWT was dried to a dew point of –20 Fahrenheit and stored in a spherical accumulator located on the south side of the building. It was lined with a rubberized diaphragm that maintained a constant pressure during test runs while serving as a vapor barrier.

Models were typically sting-mounted, with the sting secured to an arc sector that allowed changes in pitch. During its later years in service at Marshall, data from the BWT were measured by analog sensors, converted into a digital format, and punched into cards for batch processing by a computer. Optically clear windows in the sides of the test section permitted test observation, spark shadowgraphs, and schlieren photography.

HISTORY

The BWT's story begins in Peenemünde, Germany, where Wernher von Braun had secured approval to build a supersonic wind tunnel that would support his efforts to develop the V-2 ballistic missile. Aerodynamicist Rudolf Hermann recruited and directed the team that designed and built a 15.7- by 15.7-inch blowdown tunnel with interchangeable nozzles designed for Mach numbers of 2.5, 3.1, and 4.4. The tunnel employed a 40-foot-diameter vacuum sphere to draw atmospheric air through the nozzle and test section, with typical run times of 20 seconds. In spite of numerous difficulties, Hermann's team had the tunnel operational in spring 1939, but unexpected problems emerged. Condensing water vapor in the nozzle necessitated the addition of a silica-gel honeycomb in the inlet to dry the air, and difficulties in determining and machining the correct nozzle profiles restricted tunnel operation to the Mach 2.5 nozzle only until at least 1942. In spite of these difficulties, the tunnel ultimately worked well and contributed key aerodynamic data to the program. It also served as a prototype for additional supersonic tunnels at Peenemünde and Kochel between 1943 and 1945.[3]

At the end of World War II, a program named "Project Paperclip" brought many of the German rocket engineers and technicians to the United States, along with captured V-2 missiles, missile parts, and a cache of drawings and documents concerning the German rocket program. While von Braun and many of his associates ended up at Redstone Arsenal, Hermann worked as a consultant to the Air Force in Dayton,

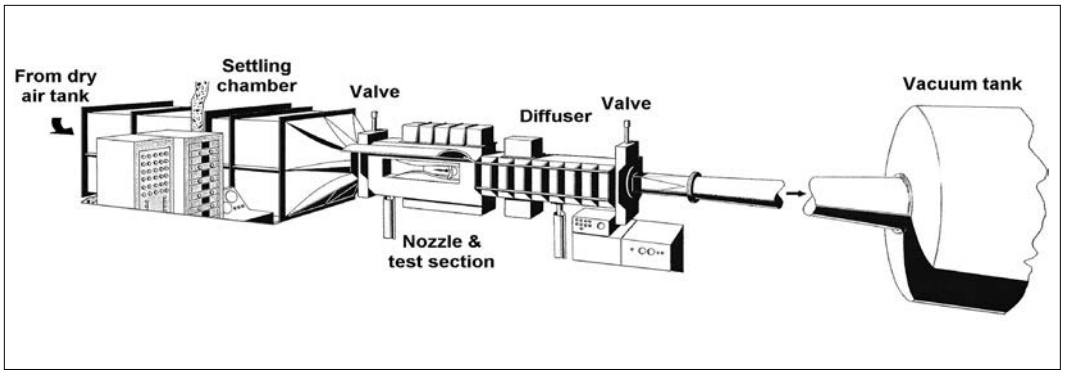
Ohio, and later as a professor at the University of Minnesota, but his supersonic wind tunnel knowledge was available to the von Braun team. (Hermann ultimately moved to Huntsville, Alabama, in 1962, well after the Redstone tunnels were in operation.)[4]

Shortly after relocating to Redstone in 1950, the team began to outline the facilities they would need to develop the Army's first major guided missiles. One of the earliest items on their list was a supersonic wind tunnel. The arsenal had an 18- by 18-centimeter supersonic tunnel used for investigating artillery shell shapes, but it was not suitable. By 1950, the NACA had several supersonic wind tunnels in operation and had developed the slotted wall that made transonic tunnels possible, but von Braun's team and NACA personnel did not exchange information. Thus, the expatriate Germans relied on their own experience and, not surprisingly, designed and built a tunnel that bore a strong resemblance to the ones they had pioneered in Germany.[5]

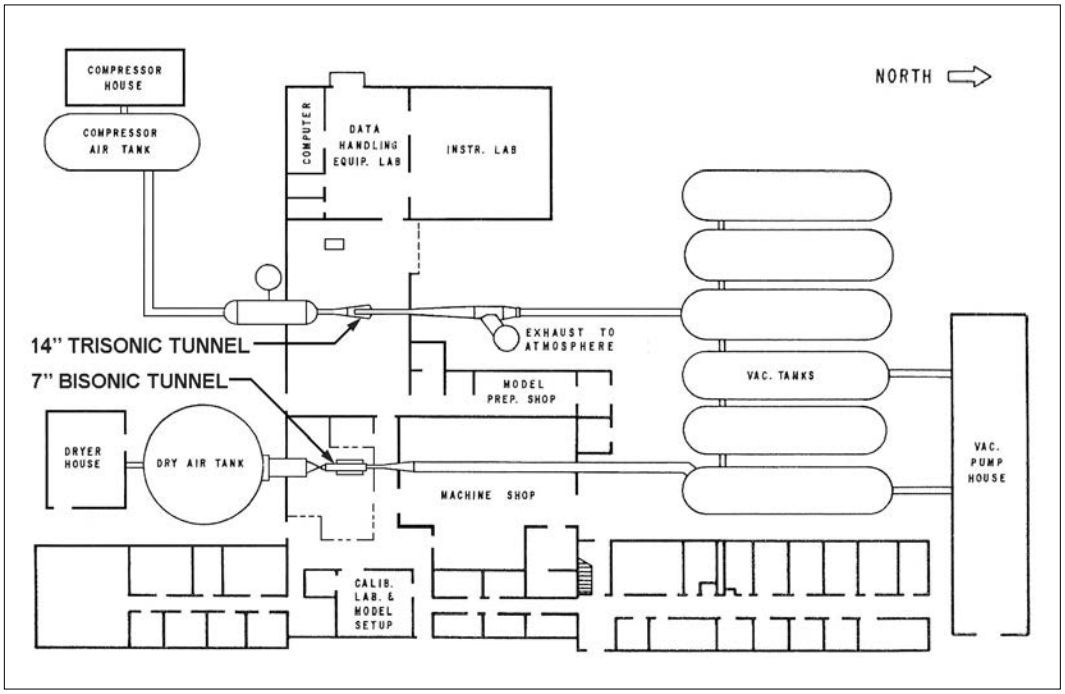
With a 7- by 7-inch test section, the BWT was the same size as both the arsenal's tunnel and one of the smaller Peenemünde tunnels, and its interchangeable supersonic nozzles produced Mach numbers very close to those of the Peenemünde tunnel. Because of the team's experience, the construction and setup of the BWT went quickly and smoothly, and it entered service in 1951. The tunnel's engineers and operators soon realized that they could achieve not only supersonic speeds, but subsonic speeds as well by removing any supersonic nozzle and carefully adjusting the diffuser's second minimum. The ability to operate at both sub- and supersonic speeds soon earned the BWT its "Bisonic" name. (Not having slotted, or perforated, walls, the BWT could not operate in the transonic range.) Throughout the 1950s, the BWT saw extensive testing of Redstone and Jupiter models to refine their aerodynamic shape and performance.

Missile development was at the forefront of American defense activities during the early years of the Cold War, and the Army sought to expand its work in this area, including the construction of new research facilities at Redstone. As early as 1952, study groups had recommended a second wind tunnel. The GMDD had looked at moving a tunnel to Redstone from its Aberdeen Proving Ground in Maryland but decided instead to build a new 14-inch tunnel, the TWT.

After the TWT fully entered service in 1958, the BWT's smaller size began to limit its usefulness for testing models of proposed missile designs, and its bookings declined. During the 1960s, after the Redstone Arsenal wind tunnel complex had become part of NASA's Marshall Space Flight Center, most of the BWT's runs involved basic aerodynamic studies, evaluations of different jet vane designs, and flight instrument calibrations. The BWT continued in this service until 1975, when it was given to Auburn University's Department of Aerospace Engineering. There it replaced a primitive 6-inch supersonic tunnel, and it remains in service supporting the university's academic program.[6]

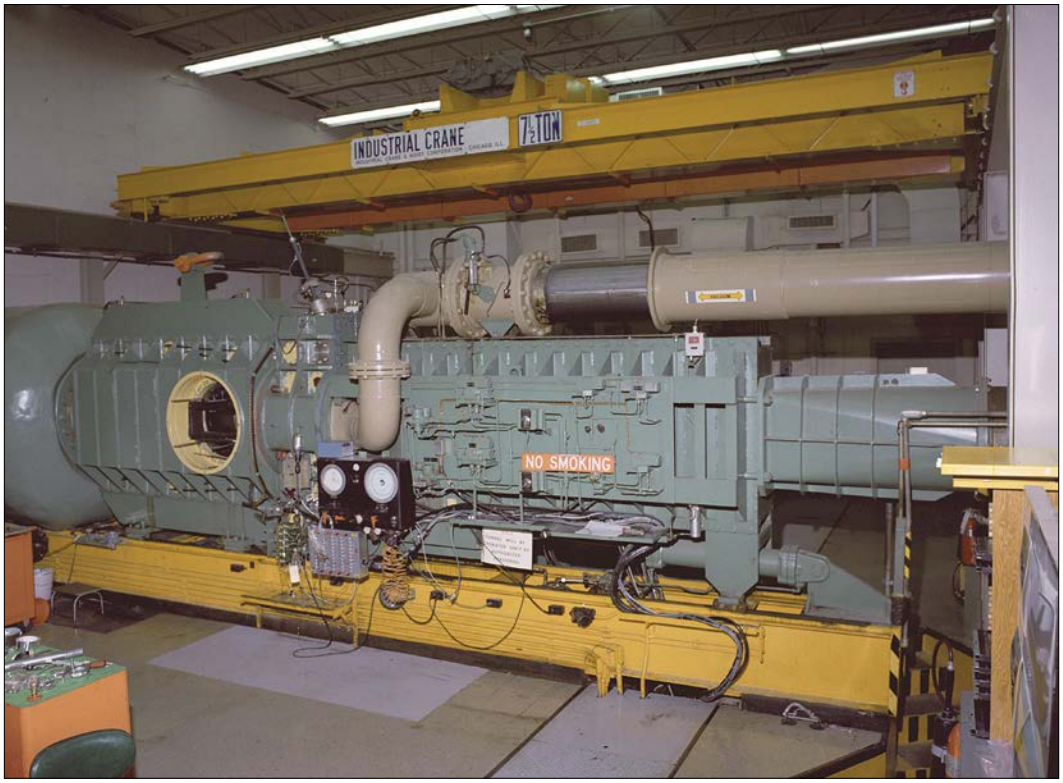


The Bisonic Wind Tunnel's nozzle and test section could be changed to produce different test speeds in two ranges. Its flow was from a dry air reservoir (not shown) at left to a bank of vacuum tanks at right. (Image credit: NASA MSFC-BWT-1)



The first floor plan of Building 4732 shows how the 7-Inch Bisonic and 14-Inch Trisonic tunnels fit in the facility. Both tunnels used the same bank of vacuum tanks. The 7-Inch Bisonic Tunnel was removed and donated to Auburn University in 1975. (Image credit: NASA TM X-64624, Fig. 2)

14- BY 14-INCH TRISONIC WIND TUNNEL



This view shows the supersonic test section installed in the Trisonic Wind Tunnel. The S-shaped duct is the suction line for the transonic test section's plenum. Note the bridge crane used for test section changes. The TWT's control console is just out of sight to the left. (Photo credit: NASA MSFC-8891417)

SIGNIFICANCE

The 14- by 14-Inch Trisonic Wind Tunnel (TWT) was the third wind tunnel built at the Redstone Arsenal by the United States Army's Guided Missile Development Division (GMDD), which became the Army Ballistic Missile Agency (ABMA) in 1956. It was one of the first tunnels to be capable of subsonic, transonic, and supersonic speeds. The TWT was one of the Redstone facilities transferred to NASA in 1960.

DESCRIPTION

The TWT is an open-circuit, blowdown tunnel with a closed test section and three interchangeable nozzles for different operating conditions. Located in Building 4732, the TWT utilizes its transonic block for a Mach number range of 0.25–1.96, and its supersonic block generates Mach 2.74–4.96. Both blocks have two-dimensional nozzles with fixed contours, but the top and bottom walls of the supersonic nozzle are mounted on servo-actuated hydraulic screw jacks that provide vertical adjustment for setting the desired speed. Three nozzles can be fitted to the transonic block to deliver test Mach numbers of 0.25–1.3, 1.46, and 1.96. The transonic test section has perforated walls to

manage shock reflections between Mach 0.9 and 1.3, though the feature is not needed at subsonic speeds. The perforations communicate with a plenum connected to a suction line. Both sides of the test section are fitted with optically clear windows for test observation, oil flow visualization, spark shadowgraphs, and schlieren photography. A third test section, known as the special, or base flow, test section, was constructed specifically to investigate the interactions between rocket exhaust plumes and the rear, or base, of missiles. It incorporates a plug-type nozzle that supports the base model. The tunnel's air flows around it and off the model's base as it would off the base of a missile in flight. Exhaust plume simulation is accomplished using compressed air through the model rocket nozzles at up to 1,000 psi.[7]

The diffuser's top and bottom walls have a fixed contour, but adjusting them vertically varies the speed within the subsonic range and optimizes performance in the higher-speed ranges. The model mount and diffuser section are on rails so that they can be rolled 30 inches away from the test section for model access or block changes. Technicians using a 7.5-ton bridge crane can change blocks in 20–30 minutes.

The core of the tunnel—nozzle, test section, and diffuser—features a square cross section, but the settling chamber and remaining ducts are circular, including the duct between the diffuser exit and vacuum reservoir. At the approximate midpoint of that run, a junction allows the flow to be diverted through a muffled stack to the atmosphere when test conditions permit. A servo-actuated gate valve at the entrance to the settling chamber is the primary control element. A second valve isolates the core portion of the tunnel from the vacuum system.

The TWT's inlet air is produced by a dedicated three-stage, 1,500-horsepower air compressor located in an auxiliary building and stored in a horizontal, 6,000-cubic-foot, cylindrical tank. The air is dried by an activated alumina dryer to a dew point of −40°F prior to entering this tank. A pipe conveys the air to the tunnel's settling chamber, and an accumulator connected to the line absorbs pneumatic shocks and maintains a uniform pressure during test runs. Fully charging the supply tank to 500 psi typically takes 15–20 minutes, but the compressor can be supplemented with 3,500-pound-per-square-inch air from the plant air system if necessary.

The TWT's vacuum reservoir consists of a bank of six interconnected, cylindrical, steel tanks with semielliptical ends mounted horizontally on concrete supports. This 42,000-cubic-foot vacuum reservoir had been installed with the BWT, and it was adequate to serve both tunnels prior to the BWT's removal in 1975. It continues to serve the TWT. Two 250-horsepower, rotary vacuum pumps in an adjacent pump house evacuate the tanks to 0.019 psia prior to a test run. This permits run times of 60–90 seconds with the transonic block, or 45–50 seconds when running at supersonic speeds. Multiple runs of shorter duration can be made before a re-evacuation is required. As many as 30 runs can be made during an 8-hour shift, making the TWT a very productive facility.

Models are typically sting-mounted, with the sting secured to a hydraulically actuated arc sector that allows changes in pitch of up to ±10 degrees during runs. Mounting

the model rotated 90 degrees yields changes in yaw, if desired, and a set of offset stings is available that can change the initial angle of attack by 6, 8, or 15 degrees. During its early years in service, data from the BWT were measured by analog sensors, converted into a digital format, and punched into cards for batch processing by a computer, but modern sensors and data acquisition equipment have been installed over the years to automate the process.

HISTORY

The TWT was a product of the Cold War. Missile development remained at the forefront of American defense activities throughout the Cold War, and the three main branches of the armed services competed for influence and the resources needed to lead the development of the new technology. With Wernher von Braun's team of expatriate Germans, the Army initially held an advantage and sought to expand its work, including the construction of new research facilities at Redstone Arsenal. As early as 1952, a GMDD study had recommended another wind tunnel and investigated the relocation of a 15- by 20-inch tunnel from the Army's Aberdeen Proving Ground to Redstone, but it ultimately chose to build a new tunnel to meet its specific needs.[8]

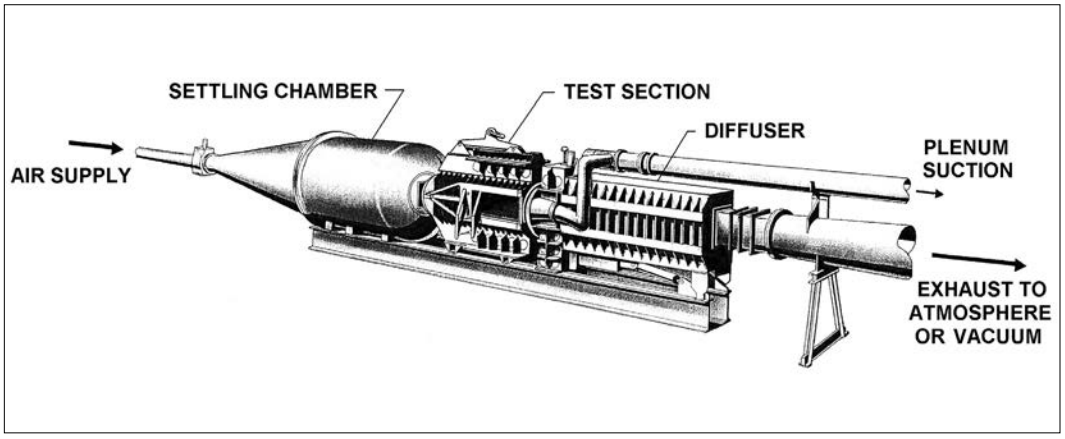
With the decision made to build a new facility, Oscar Holderer and Herschel Belew led a team of GMDD engineers that designed it. They began in 1954, and the design effort took about a year to complete. Their goal was a moderately sized tunnel with a practical, flexible design that would support primary aerodynamic studies of missile concepts and designs in an economical manner. This meant a tunnel designed to perform two types of tests: aerodynamic stability and pressure distribution. Accordingly, the team eschewed complex features, such as flexible-wall nozzles and elaborate pressure and temperature controls, and concentrated on straightforward solutions to reach their goal. Experience with the BWT provided a reasonable foundation for the design, particularly the concept of using a blowdown tunnel with changeable nozzle-test section blocks for different speed ranges, as well as areas that needed improvement, such as adding transonic capability. They also made the maximum use of existing resources built for the BWT. When complete, their drawings went to the Army's Watertown Arsenal in New York, which fabricated the core components over the next several months.

In 1956, while the TWT was under construction, the Army folded the GMDD into a new organization, the ABMA, partly in response to a Department of Defense policy change that redefined the Army's role in missile defense. TWT construction was not affected, but when the tunnel opened, it did so as part of the Aeroballistics Division of the ABMA.

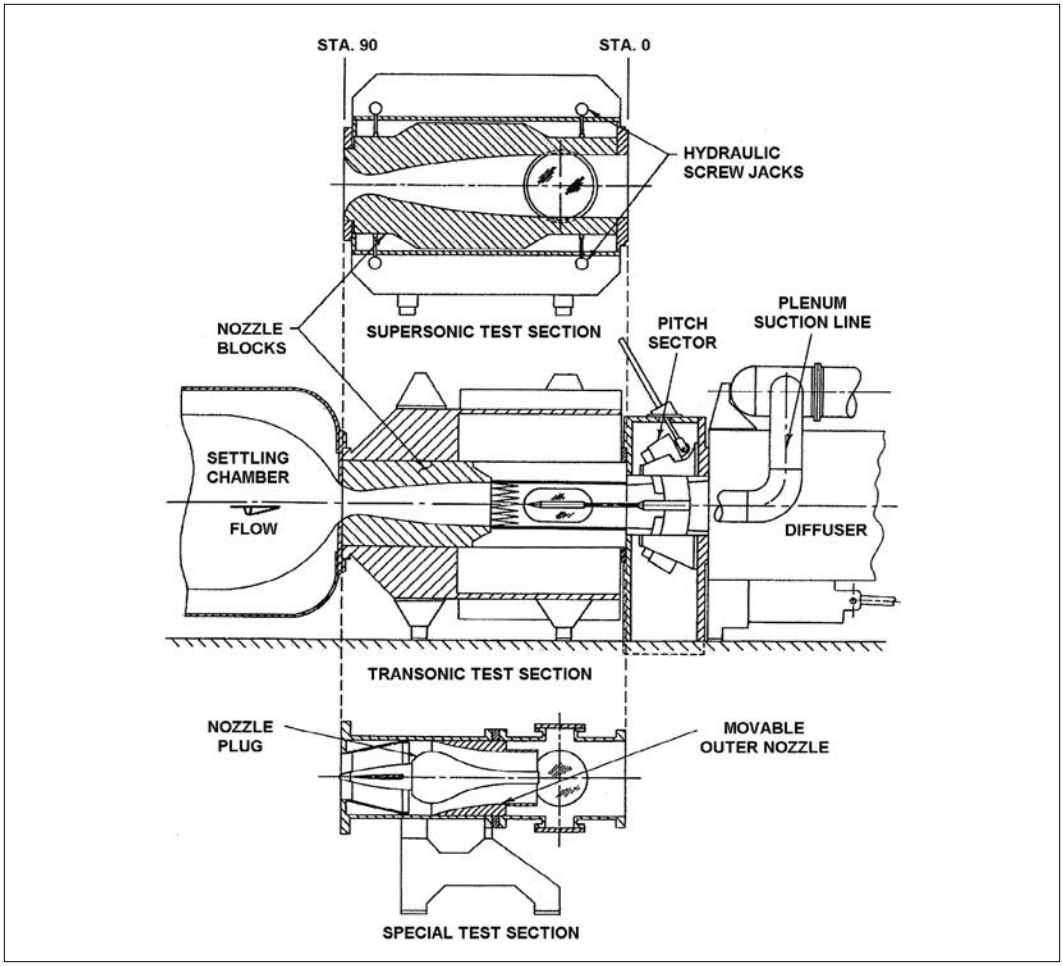
The TWT opened early in 1957 with only its transonic test section. Supersonic nozzles are more difficult to design and build, and the fixed contour-movable-wall design Holderer and his team wanted took about another year to design, build, and perfect. The proper settings for the jacks over the Mach number range are now pre-programmed into the tunnel's process control system, greatly simplifying test setup.[9]

The TWT quickly went to work testing such Army missiles as the Jupiter, the Jupiter-C, and Juno I, and the modified Jupiter-C—itself a modified Redstone—that launched America's first satellite, Explorer 1, into orbit on 31 January 1958. The creation of NASA in 1958 ultimately led to the TWT being transferred to the new agency as part of Marshall Space Flight Center in 1960. In reality, the administrative change made very little difference in the tunnel's operation; it tested "launch vehicles" instead of "missiles." The nature of the tests stayed largely the same, but the main vehicles of interest were NASA's Saturn I and IB, followed by the Saturn V Moon rocket. As the Apollo program came to an end in 1972, the TWT was hosting tests of various concepts for the Space Transportation System, commonly known as the Space Shuttle. These tests vividly illustrated one of the tunnel's key advantages. Its size was ideal for a large amount of preliminary and early design-related testing, because both models and operation of the tunnel were much quicker, cheaper, and easier to build and perform than larger, more-powerful tunnels, yet its performance envelope was well suited to tests that involved the first few minutes of flight, including the effects of changing exhaust plumes on the vehicles. Some concepts that were ultimately rejected saw testing only in the TWT.[10]

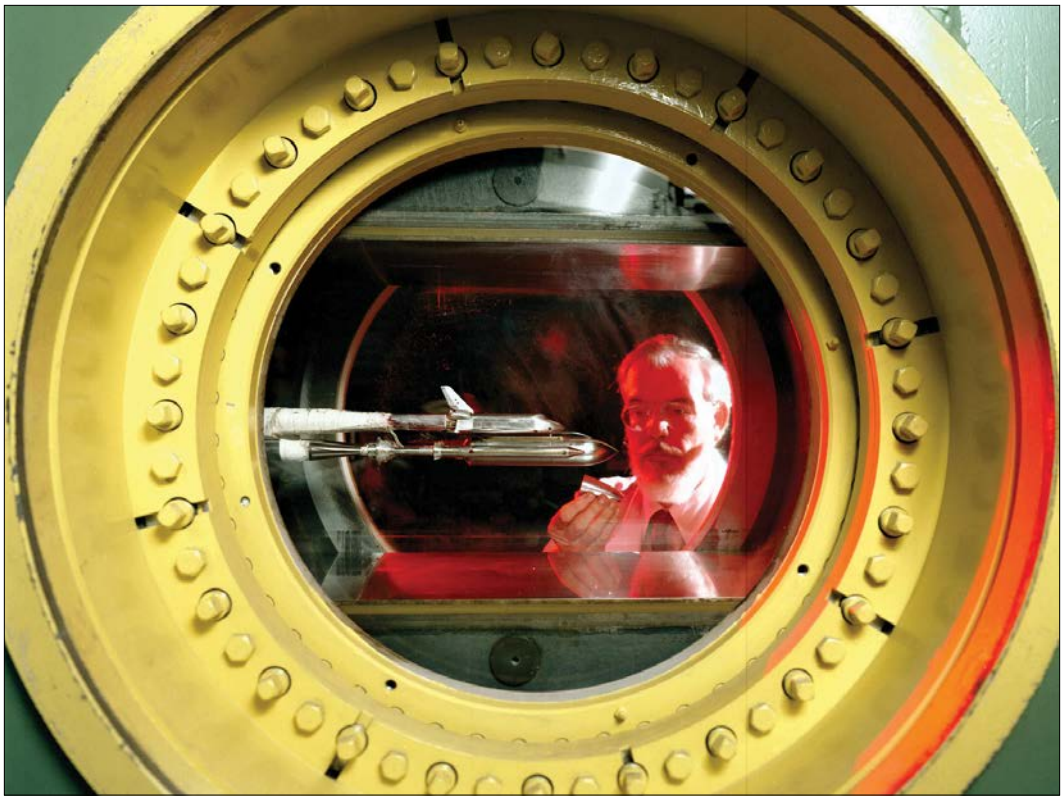
The TWT continues to perform this role today, having hosted much of the early testing of the Constellation Program's Ares I Crew Launch Vehicle stack. Some of this testing involved the staging process, where the spent first stage is jettisoned. In recent years, the TWT has been used for SLS testing. The TWT remains in active service with Marshall's Aero-Astrodynamics Laboratory.[11]



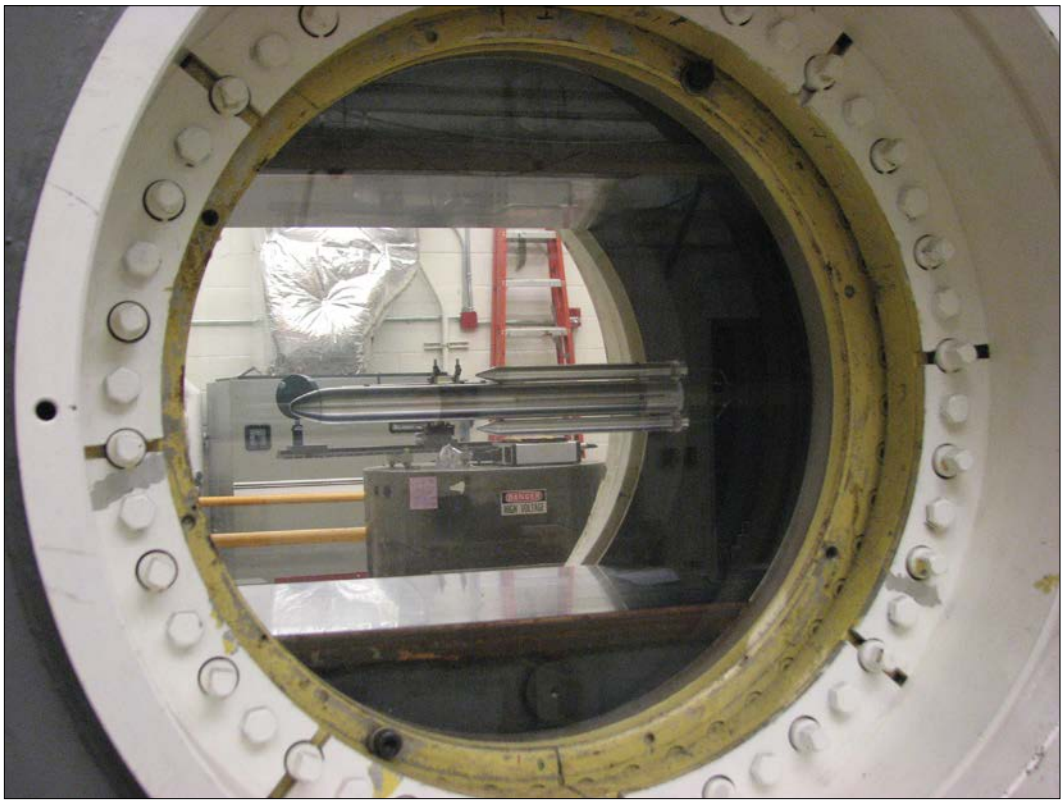
The TWT's nozzle and test section could be changed to produce different test speeds in three ranges. Its flow was from a compressor and air reservoir at left to a bank of vacuum tanks or an atmospheric exhaust at right. (Image credit: J. Lawrence Lee)



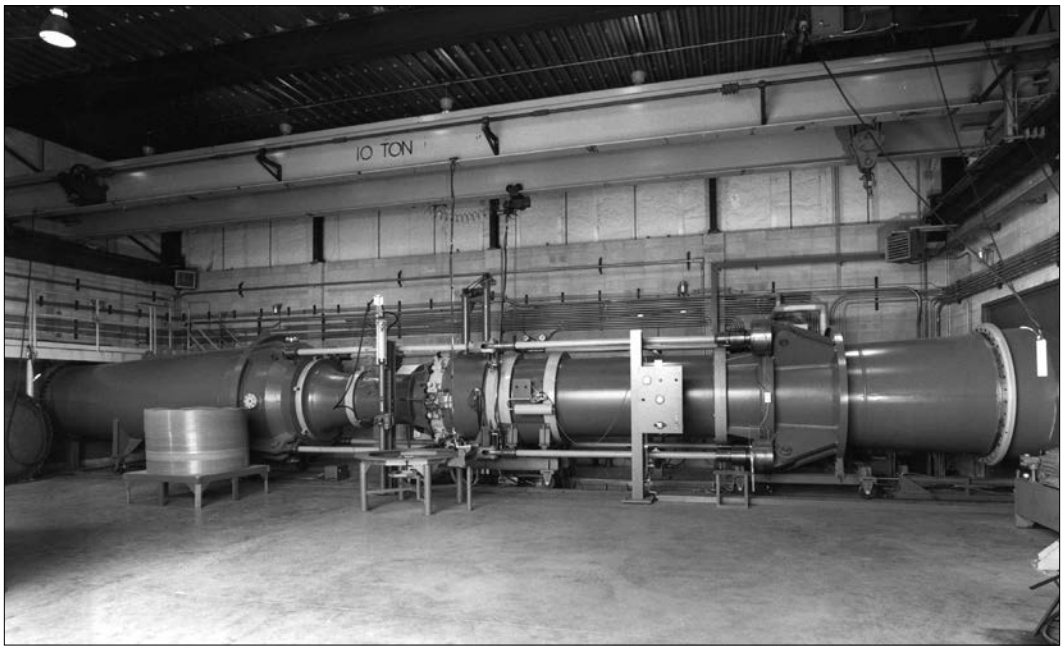
The three interchangeable nozzle-test section blocks are shown here. The transonic test section can be operated subsonically to give the TWT its "trisonic" capability. The special, or base flow, test section, designed for investigations of rocket exhausts and their effects on the rear of vehicles, is now rarely used. The pitch sector adjustment for the sting mount is hydraulically actuated. It and the diffuser can retract. (Image credit: NASA TM X-64624, Fig. 4)



These two views of the supersonic test section illustrate the types and sizes of models typically tested in the 14- by 14-inch TWT. The models are a Space Shuttle stack (top) and a heavy-lift configuration of the Space Launch System rocket (bottom). Both models are mounted on stings. (Photo credits: NASA MSFC-8445212 and TWT img_4401)



HIGH REYNOLDS WIND TUNNEL



The core portion of the High Reynolds Wind Tunnel is located in Building 4775. Some of the tunnel's sections can be moved longitudinally on a track to access the model and rupture disk, and the overhead bridge crane was used for nozzle and test section changes. Flow was from left to right, and the rupture disk was located at the fifth band from the left. (Photo credit: NASA MSFC-HRWT-3)

SIGNIFICANCE

The High Reynolds Wind Tunnel (HRWT) is the only Ludwieg tube ever operated by NASA, and it was the last major wind tunnel constructed at Marshall. It was designed and built primarily to test rockets and launch vehicles for their response to aerodynamic loads at speeds of up to Mach 3.5.

DESCRIPTION

The HRWT is a type of impulse tunnel known as a Ludwieg tube. It is a simple and relatively inexpensive device for generating a short-duration supersonic flow. Fabricated of steel, the HRWT consists of a supply tube with one end capped, six (originally four) fixed-contour nozzles designed for Mach numbers of 0.25–3.5, either a transonic or supersonic test section, a model support section with an arc-sector-mounted sting, a diaphragm section fitted with a rupture disk, a diffuser, and a receiver sphere. The entire facility is considered to be Building 4775, though only the core portion is located inside the steel-framed structure.[12]

Like other impulse tunnels, a Ludwieg tube like the HRWT produces a short burst of air that flows past a model at a high speed, but a Ludwieg tube does this somewhat differently than impulse tunnels, which initiate their flows explosively to generate a high-velocity pulse of gas, essentially a shock wave, that passes the model. In such

tunnels, the model is initially inside an evacuated test section (or, in counterflow tunnels, shot through the previously evacuated test section), and the gas expands into and through the test section to a dump tank. In a Ludwieg tube, the test section is initially pressurized along with a long, straight tube that serves as the supply reservoir of test gas, usually air. When a diaphragm *downstream* from the model is ruptured, two waves are created. One propagates downstream into the low-pressure, or evacuated, receiver as airflow begins. The second is an expansion wave that propagates *upstream* through the supply tube, where it reflects off the end and assists the previously pressurized air that is starting to flow toward the receiver in establishing a stable, subsonic flow. This flow must then pass through a nozzle and flow past the model to reach the receiver. The model, which was initially inside the pressurized volume, is exposed to high-pressure flow, and the combination of high pressure and high velocity is how the tube generates high Reynolds numbers. In the HRWT, this process yields steady-flow test times of between 150 and 500 milliseconds and Reynolds numbers of up to 200 million per foot, with body diameter being the usual dimension of interest.

The HRWT's transonic nozzle could produce subsonic and transonic speeds between Mach 0.25 and 1.35. The tunnel opened with three supersonic nozzles contoured for Mach numbers of 1.4, 1.7, and 2.0, but nozzles for Mach 2.75 and 3.5 were added later. All five nozzles are axisymmetric. Each nozzle was fabricated as an interchangeable block, with only one installed at a time. Operators used a 10-ton bridge crane to change these nozzle blocks and the two test section blocks. The transonic test section is perforated, and its porosity can be varied between 0 and 10 percent of the surface area. It is 32 inches in diameter by 100 inches long. Each supersonic nozzle also has a diameter of 32 inches, but these nozzles are only 64 inches long. A spacer is added with them to maintain the tunnel's overall length and test section location. A settling chamber is located between the supply tube and nozzle to reduce turbulence into the nozzle. It is a 20-foot-long truncated cone that expands from the supply tube's 4-foot, 4-inch diameter to a maximum diameter of 6 feet, 6 inches. An entrance cone with an 8-degree included angle leads to the nozzle inlet. The rupture disks were cut from a sheet of biaxially oriented polyethylene terephthalate, commonly referred to by its duPont trade name, Mylar.

The HRWT's supply tube is a 52-inch-diameter, 400-foot-long steel tube. One end has a hemispherical cap, and the other is connected to the settling chamber. Most of it is outside the building's west side, supported by 14 concrete piers. Since the tube is anchored at the settling chamber, the support piers have roller saddles to accommodate expansion and contraction due to thermal heating. (The end of this tube moves almost 3.5 inches during a 100°F change in temperature.) Before each test run, the supply tube, settling chamber, nozzle, and test section were charged with clean, dry air known as "missile grade" air from a central system to a pressure between 550 and 700 psi, depending on the test setup and requirements.

The 50-foot-diameter steel receiver sphere is supported by a steel ring and concrete foundation. The end of the diffuser has a 45-degree corner so that it penetrates the sphere

radially. It terminates with a hemispherical cap near the sphere's center, and the last portion of the duct is perforated all around to distribute the flow evenly throughout the sphere. The sphere, which could be sealed off by valves to form a vacuum chamber, normally operated at atmospheric pressure, and a muffler at its top point reduced the noise level of exhausting air during runs.

Models were sting-mounted, and the sting was supported on an arc sector that could change the pitch between 0 and –18 degrees. Six-component, strain-gage balances designed into the models measured the aerodynamic forces and moments on them. The HRWT, like all Ludwieg tubes, generated high aerodynamic forces and moments on fairly small models, and the models had to be designed to withstand them. The HRWT produced longitudinal forces as high as 4,000 pounds, normal forces up to 13,500 pounds, and a maximum rolling moment of 5,000 foot-pounds. While bodies of revolution could be built that were capable of handling such loads without damage, the thin wings or fins of models that would fit into the test sections generally could not, resulting in plastic distortion or complete failure. Thus, the HRWT was limited to such items as missile bodies and reentry vehicles.

HISTORY

The HRWT resulted from a growing need at Marshall to evaluate launch vehicle shapes through the transonic and low-supersonic flight regimes in an inexpensive manner, but also under conditions that produced high Reynolds numbers. High Reynolds numbers would allow the vehicle designers to match, or at least closely approach, those of actual flight, thus giving them greater confidence that the parameters measured using wind tunnel models could be scaled up to the full-size vehicles. The Trisonic Tunnel at Marshall, and a number of other tunnels at other NASA centers, could produce the needed speeds, but their Reynolds numbers were well below desirable values.

This was a common problem during the 1950s, and it remains a challenge for wind tunnel designers. Higher Reynolds numbers are usually achieved by raising the air's pressure to increase its density and/or lowering its temperature to reduce its viscosity. This requires strong and/or insulated tunnel construction with a complex pressurization and/or refrigeration system. Responding to a European competition to devise a means of inexpensively producing high Reynolds numbers, German engineering professor Hubert Ludwieg proposed the design that bears his name in 1955. Ludwieg tubes are not numerous, but they have been useful in certain situations. During the 1960s, Marshall engineers developing launch vehicles of unprecedented size and power found one to be an economical tool for addressing a major concern. The structural weight of the Saturn series had to be as low as possible, which meant low factors of safety. This could be done with confidence only if the engineers fully understood the maximum longitudinal and transverse aerodynamic loads the vehicle would experience, including the complex loads resulting from flow separation. The longitudinal loads peak, a condition known as "Max Q," at Mach 1, but transverse loads from upper atmospheric

winds can be higher at other speeds. The Saturn vehicles had to be able to safely endure any combination of these loads.[13]

Marshall engineers, led by A. R. Felix, determined that a Ludwieg tube could provide very useful force and moment data for these conditions, and they received funds to build the HRWT in the late 1960s. Fabrication and erection required about one year, and the facility was completed in 1969. Fine-tuning the nozzles and calibrating the tunnel took over a year, but the HRWT was ready for service near the end of 1970. This was, of course, too late to help the Saturn I and Saturn V programs, but the engineers believed it would be useful during the development of future launch vehicles. This belief was proven true, or at least partially true, during the development of the Space Shuttle. Tests generated valuable data about the aerodynamic forces on the solid rocket boosters (SRBs), particularly after jettisoning at approximately Mach 4, when they tumble as they begin their ballistic descent to the ocean.[14]

The HRWT saw intermittent use after the Space Shuttle became operational in the early 1980s, but it was maintained in an operational condition until limits in NASA's budgets during the 1990s caused the agency to evaluate the financial viability of each of its wind tunnels. NASA decided to mothball the HRWT by the end of the decade. Since that time, some useful fittings and instruments have been cannibalized for use elsewhere at Marshall, but the essentially intact, though largely abandoned, tunnel survives in place.

The HRWT's 390-foot-long tube was pressurized to 600–700 pounds per square inch before each test, and the distant sphere was at atmospheric pressure or evacuated. Rupturing a disk produced a high-speed, high–Reynolds number flow. Note the roller supports to accommodate thermal expansion. (Photo credit: MSFC-9513784)

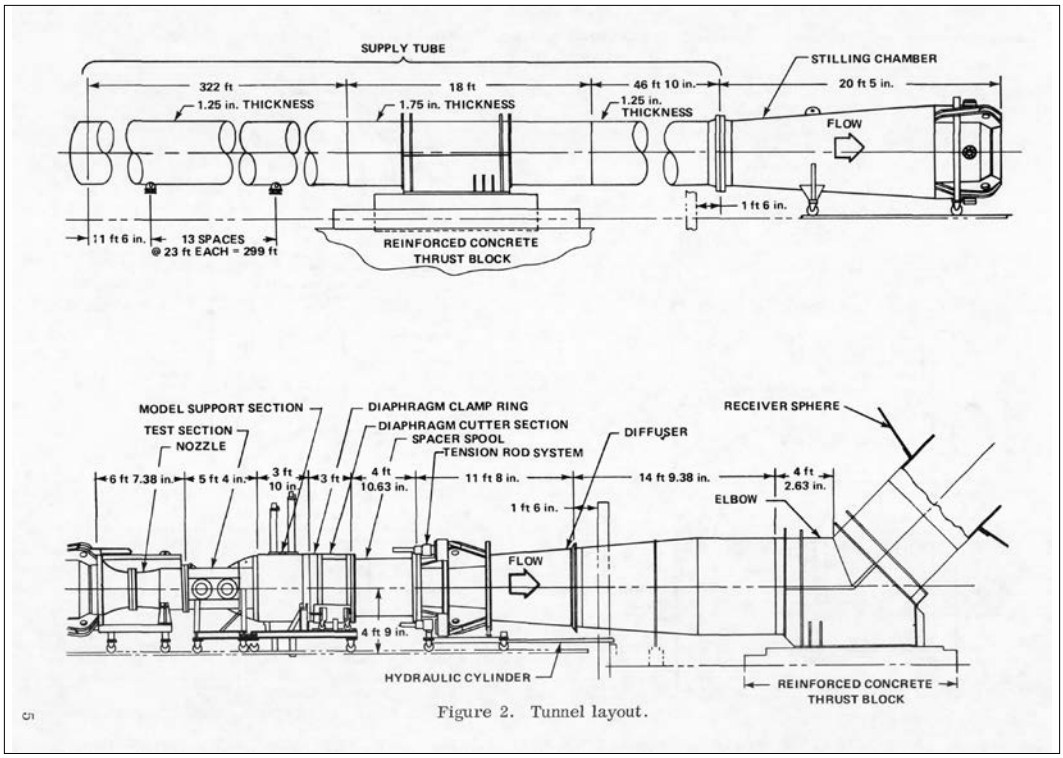
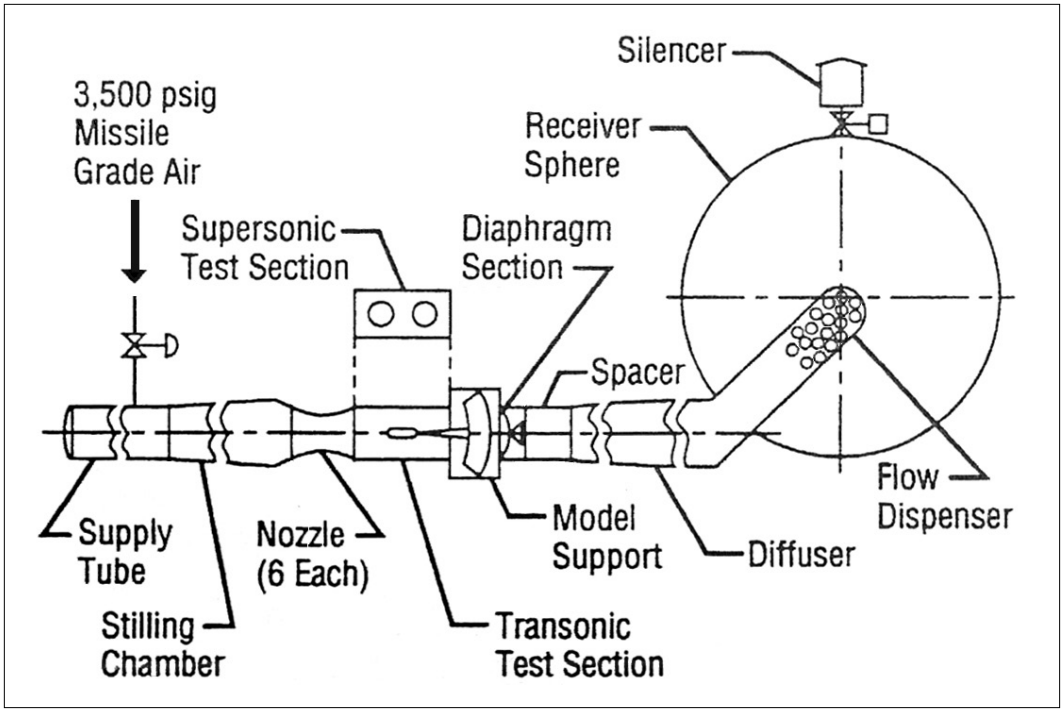
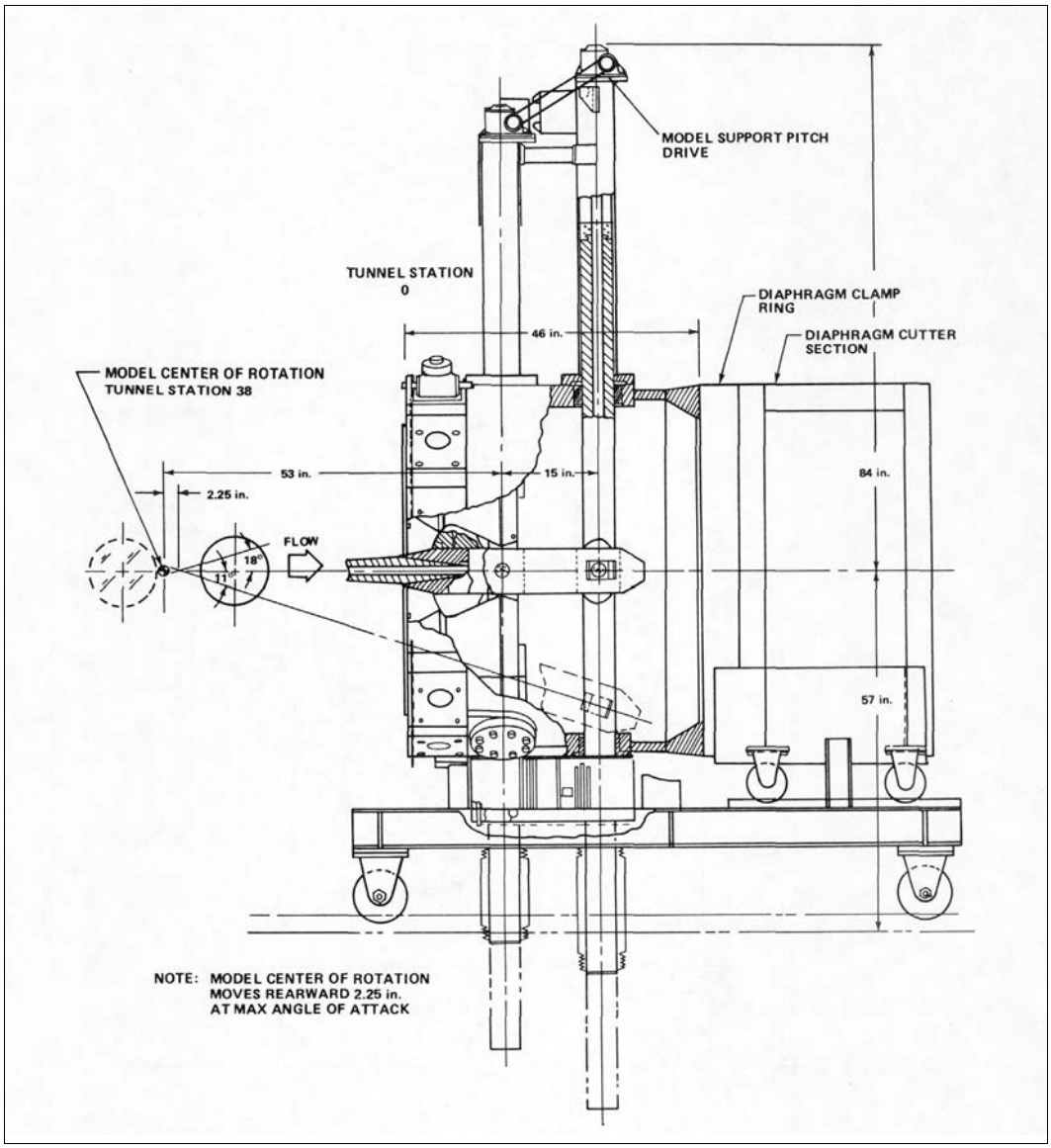


Figure 2. Tunnel layout.

These schematic drawings show the intrinsic simplicity of the HRWT's Ludwieg tube. When a disk in the diaphragm section was ruptured, compressed air in the long supply tube at left rushed through the nozzle, past the model, and into the evacuated receiver sphere at right, generating a steady flow with a high Reynolds number, but also very large aerodynamic forces, for up to one-half second. (Image credits: NASA TM X-64831, Fig. 2 and J. Lawrence Lee)





The model support sting can be seen in the center of this view of the HRWT's opened test section. Note the pendant control for the bridge crane hanging at left. (Image credit: NASA TM X-64831, Fig. 6)

ENDNOTES

1 For a thorough history of Marshall, not including the Army era, see Andrew J. Dunar and Stephen P. Waring, *Power to Explore: A History of Marshall Space Flight Center, 1960–1990* (Washington, DC: NASA SP-4313, 1999).

2 Descriptive and performance data were compiled from "Experimental Aerodynamic Facilities," an undated (ca. 1962) document by the Marshall Aerodynamics Div., Facilities Branch; NASA Marshall Space Flight Center History Office; and Vernon F. Callahan, Jr., ed., *Space Guide: A Basic Guide to NASA* (Fairfax, VA: Callahan Publications, 1962), p. 65; and "NASA-Marshall Space Flight Center Fact Sheet," 5 Aug. 1966, NASA Marshall Space Flight Center History Office.

3 Michael J. Neufeld, *The Rocket and the Reich: Peenemünde and the Coming of the Ballistic Missile Era* (Cambridge, MA: Harvard University Press, 1995), pp. 86–89.

4 Charles A. Lundquist and Anne M. Coleman, "Rudolf Hermann, Wind Tunnels and Aerodynamics," *Acta Astronautica* 62, nos. 8–9 (April–May 2008): 463–470.

5 Anthony Springer, "The George C. Marshall Space Flight Center's 14 × 14-Inch Trisonic Wind Tunnel: A Historical Perspective," *Paper 94-0539* (Reston, VA: AIAA, 1994), pp. 3–4.

6 Ibid., p. 4.

7 Descriptive and performance data were compiled from "Experimental Aerodynamic Facilities," an undated (ca. 1962) document by the Marshall Aerodynamics Div., Facilities Branch, NASA Marshall Space Flight Center History Office; Erwin Simon, "The George C. Marshall Space Flight Center's 14 × 14-Inch Trisonic Wind Tunnel Technical Handbook," *Technical Memorandum X-64624* (Washington: NASA, 1975); "NASA-Marshall Space Flight Center Fact Sheet," 5 Aug. 1966, NASA Marshall Space Flight Center History Office; and Paul E. Ramsey, "An Investigation in the NASA MSFC 14-Inch Trisonic Wind Tunnel to Determine the Pressure Distribution Over the Components of a 0.004 Scale Version of the Rockwell MCR 0074 Baseline Shuttle Ascent Configuration (IA32F)," *Contractor Report 141,808* (Washington: NASA, 1975), pp. 11–12. For details of the special nozzle, see S. V. Paranjape, J. J. McGowen, and H. A. Cikanek, Jr., "Static and Dynamic Calibrations of MSFC's Plug-Nozzle Special Test Section (Redesigned 1967)," *Contractor Report 61312* (Washington, DC: NASA, 1969).

8 A. Springer, "The George C. Marshall Space Flight Center's 14 × 14-Inch Trisonic Wind Tunnel: A Historical Perspective," *Paper 94-0539* (Reston, VA: AIAA, 1994), pp. 3–4.

9 Ibid., p. 3. Also Ramsey, *Contractor Report 141,808*, p. 11.

10 Springer, *Paper 94-0539*, pp. 5–7. Also typical reports of tests conducted in the TWT, including Ramsey, *Contractor Report 141,808*; J. D. Johnson and W. F. Braddock, "Reentry Aerodynamic Forces and Moments on the Engine Nozzle of the 146-Inch Solid Rocket Booster Model 473 in MSFC 14 × 14 Inch Trisonic Wind Tunnel (SA30F)," *Contractor Report 141,810* (Washington, DC: NASA, 1975); and A. Springer, "Experimental Investigation of Plum-Induced Flow Separation on the National Launch System 11/2-Stage Launch Vehicle," *Paper 94-0030* (Reston, VA: AIAA, 1994).

11 Author's inspection of TWT and conversation with Holly Walker, Facility Engineer, Marshall Space Flight Center, 12 Dec. 2006.

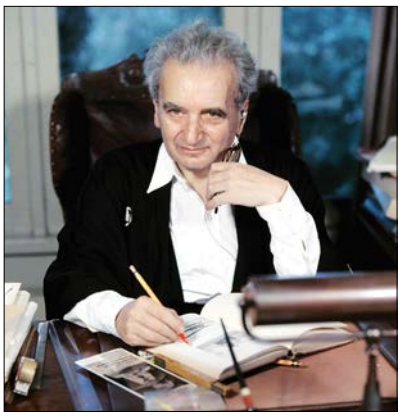
12 Descriptive and performance data were compiled from *Facilities and Equipment Capabilities Catalog, 1990*, NASA Marshall Space Flight Center History Office; A. R. Felix, "MSFC High Reynolds Number Tube Tunnel," *Technical Memorandum* X-67419 (Washington, DC: NASA, 1971); H. S. Gwin, "The George C. Marshall Space Flight Center High Reynolds Number Wind Tunnel Technical Handbook," *Technical Memorandum X-64831* (Washington, DC: NASA, 1975); and Paul E. Ramsey, "An Investigation to Determine the Pressure Distribution on the 0.0137 Scale Solid Rocket Booster Forebody (MSFC Model 467) at Angles of Attack at or Near 90° and High Reynolds Numbers in the MSFC High Reynolds Number Wind Tunnel (SA29F)," *Contractor Report 147608* (Washington, DC: NASA, 1976), p. 10.

13 Donald D. Baals and William R. Corliss, *Wind Tunnels of NASA* (Washington, DC: NASA, 1981), pp. 103–104.

14 Typical test reports include Ramsey, *Contractor Report 147608*; and J. D. Johnson and G. W. Winkler, "Force Test of a 0.88 Percent Scale, 142-Inch Diameter Solid Rocket Booster (MSFC Model Number 461) in the NASA/MSFC High Reynolds Number Wind Tunnel (SA13F)," *Contractor Report 144617* (Washington, DC: NASA, 1976).

This aerial photograph of the Jet Propulsion Laboratory was taken long after its wind tunnels had been removed. They were located on the upper (north) side of the campus, to the right of the grassy area. (Photo credit: NASA/JPL-Caltech)

JET PROPULSION LABORATORY



Theodore von Kármán, founder of the Jet Propulsion Laboratory, in 1957
(Photo credit: NASA/JPL-Caltech)

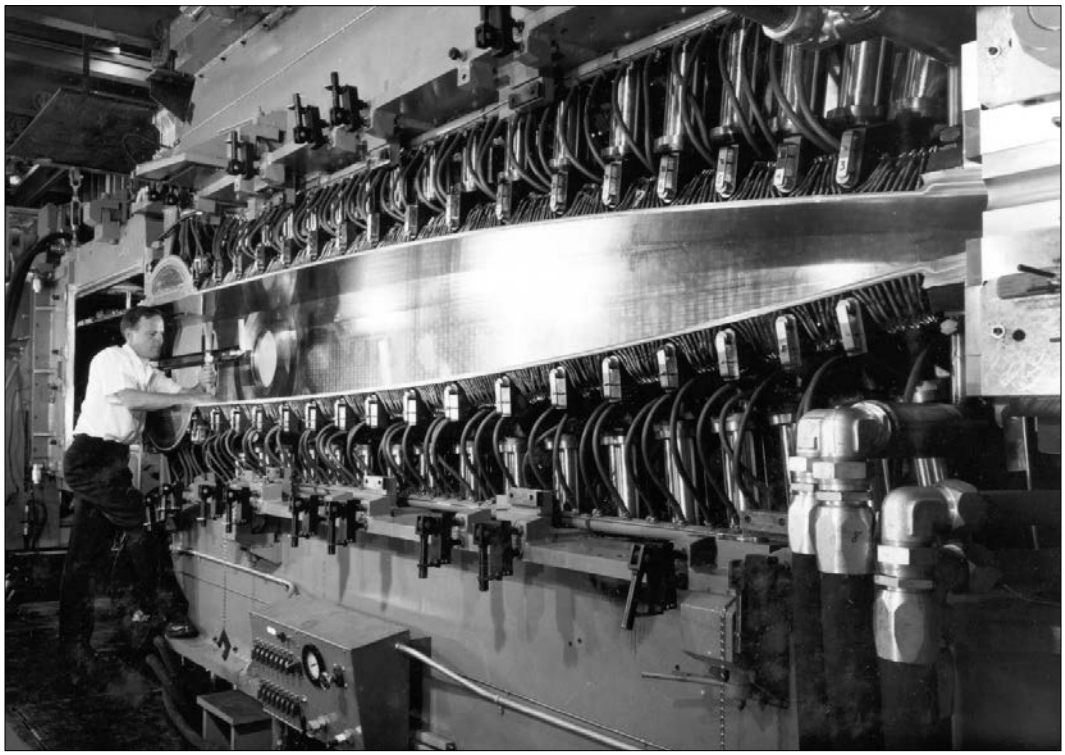
Though now known primarily as the builder and operator of America's most ambitious robotic deep space and planetary exploration vehicles, the Jet Propulsion Laboratory (JPL) began as its name suggests, as a laboratory to develop rocket engines and missiles. A group of engineering graduate students at the California Institute of Technology (Caltech) became interested in rocket propulsion, and they built and test-fired a small, liquid-fueled rocket in 1936. Renowned aerodynamicist Theodore von Kármán was the advisor to Frank Malina, one of the students who built the engine, and, intrigued by the possibilities, von Kármán convinced the Army to fund further research on a "GALCIT Rocket Project" three years later.[1] The early results were encouraging, and in 1944, the service formally established JPL as a permanent facility that Caltech would operate under contract to the Army Ordnance Department, then the Army Ballistic Missile Agency (ABMA).

Because of the noise and the inherent hazards of rocket fuel and rocket firing, Malina and his fellow students tested their rockets in a then-remote canyon known as Arroyo Seco on the northern edge of Pasadena. When JPL was formally established, the Army purchased the property through Caltech. During the late 1940s and early 1950s, JPL concentrated on the development of tactical missiles for the Army in partnership with aircraft builders, and these efforts resulted in the nation's earliest guided missiles, including the Private, Corporal, and WAC Corporal. These programs led JPL to build some of America's early supersonic wind tunnels.

Working with the ABMA, which was developing a variant of its Redstone missile to serve as a sounding rocket and satellite launch vehicle, a JPL team directed by William H. Pickering designed and built Explorer 1, the first satellite placed into orbit by the United States. Launched on 31 January 1958, the satellite collected the first data confirming the existence of the Van Allen radiation belts. The Explorer 1 project, coupled with the laboratory's early work on missile guidance systems, led JPL into the realm of uncrewed spacecraft, and this quickly became the laboratory's primary activity and area of expertise.

When NASA was formed on 1 October 1958, JPL was transferred from the ABMA to the new organization, although it continued to be managed by Caltech. Under NASA, its role was defined as the design, construction, and operation of robotic vehicles for space and planetary exploration, including certain Earth orbit missions that can benefit from the laboratory's expertise and experience. Having redefined the laboratory's mission, NASA phased out what remained of JPL's propulsion research, and its wind tunnels were disassembled and shipped to other NASA centers or scrapped. Scant evidence now exists of JPL's propulsion work, but the facility remains at the forefront of uncrewed space and planetary research. The Mariner, Surveyor, Viking, Voyager, and Mars Exploration Rover programs are just a few of JPL's innovative and highly productive missions.

20-INCH SUPERSONIC WIND TUNNEL



With one side open for access, the flexible top and bottom of the 20-Inch Supersonic Wind Tunnel's nozzle and the actuating cylinders can easily be seen. The technician is at the test section. (Photo credit: NASA JPL/Caltech P-1299A)

SIGNIFICANCE

The 20-Inch Supersonic Wind Tunnel (SWT) was one of the nation's early supersonic wind tunnels. It utilized flexible top and bottom walls to achieve a continuously variable range of supersonic speeds. It is the only major NASA tunnel to have been moved from one research center to another and placed back into service.

DESCRIPTION

When built and while in service at JPL, the SWT was a closed-circuit, supersonic wind tunnel powered by an unusual arrangement of seven compressors. It was constructed primarily of steel plate and structural shapes. Despite its name, the SWT's test section measured 18 inches high by 20 inches wide. Supersonic nozzles must be precisely contoured for a specific speed, but JPL engineers designed a nozzle that used a series of jacks to flex sheets of stainless steel and, thus, recontour the nozzle for a range of speeds between Mach 1.3 and 5.0. (For special programs, the SWT has operated at Mach 0.3–0.7 and at Mach 5.6.) The top and bottom surfaces were flexible, but both sides of the nozzle, which are flat, are on tracks so they can retract to provide access to the nozzle and the forward portion of the test section. They are bolted in place during test runs.[2]

Models were typically sting-mounted on an arc-type support that allowed pitch adjustment from –10 to +20 degrees and 350 degrees of rotation. Large-scale models of components, such as inlets, could be mounted to a windshield on the arc sector and enjoy the same range of pitch adjustment. The test section was fitted with two 24-inch-diameter optically clear windows for shadowgraph or schlieren photography, but one or both of these could be replaced with a sidewall mount. Although it was not remotely controlled, the sidewall mount allowed ±27 degrees of pitch adjustment. The SWT also featured a vertical traverse with ±15 degrees of pitch adjustment that could travel the full height of the test section. This was used primarily for wake surveys. Shadowgraph and schlieren photography equipment for flow-field visualization was available as well. The SWT included a six-point balance, and numerous pressure and temperatures could be recorded as well. After 1954, all data from the sensors were digitized, either automatically or manually, and some data processing was available using JPL's ElectroData 202 computer system. When a Burroughs, ElectroData Division, 220 computer replaced the 202 in 1958, the older computer was largely dedicated to the support of JPL's wind tunnels. A Digital Equipment PDP-1, the first commercial minicomputer, was later installed to furnish the tunnel's primary data-processing support.[3]

The SWT's power came in the form of compressed air from a central compressor plant that housed 11 centrifugal compressors and an axial-flow vacuum pump. For the SWT, a train of seven centrifugal compressors, A through G, was normally used, and they were connected in an uncommon configuration for wind tunnels. Air from the diffuser first entered two parallel compressors, A and B. Driven by 4,000-horsepower motors, they had a compression ratio of 2.5:1. The combined output from Compressors A and B entered Compressor C, which was identical to A and B. The output from Compressor C was again split and fed to two pairs of series-connected compressors, D and E, and F and G. Each of these compressors had a 2.1:1 compression ratio and was driven by a 1,000-horsepower motor. The outputs of compressors E and G were combined and conveyed to the settling chamber, or what JPL engineers called the "supply section." The total compression ratio for this train of compressors was slightly over 27.5:1, and their drive motors totaled 16,000 horsepower. The axial-flow vacuum pump simulated altitude by reducing the ambient pressure inside the circuit. A two-stage refrigeration and activated-alumina air system at the compressor plant dried the makeup air.

HISTORY

During the late 1940s and early 1950s, JPL focused on developing tactical missiles for the Army in partnership with aircraft builders, and these efforts resulted in the nation's earliest guided missiles, including the Private, Corporal, and WAC Corporal. These missile programs led JPL to build two of America's early supersonic wind tunnels, one of which was the SWT.

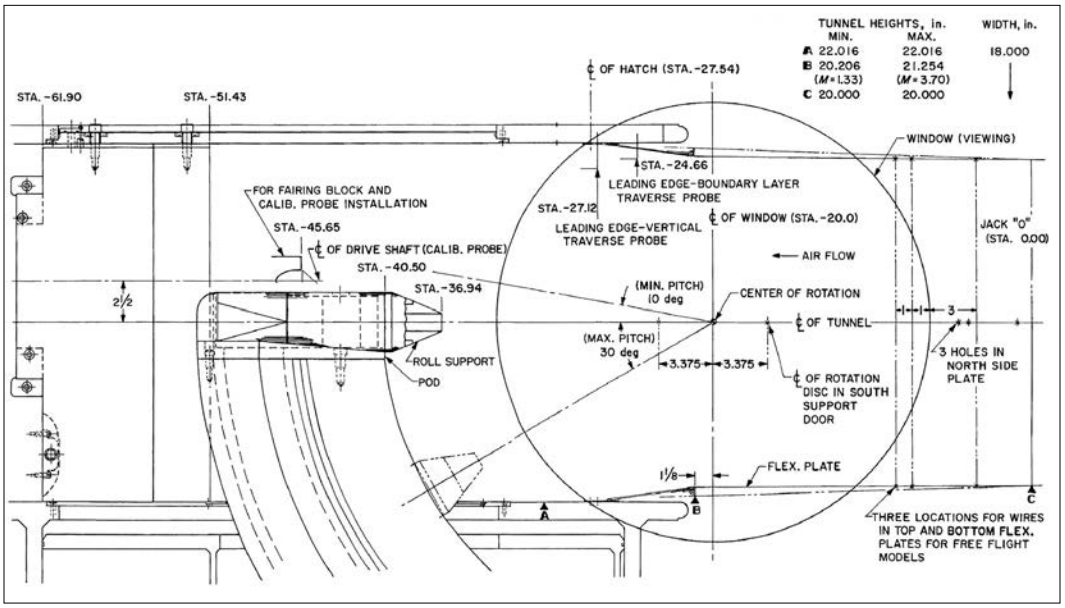
As these projects progressed, engineers at JPL realized that they needed a wind tunnel capable of reaching speeds of Mach 4, or higher, to test and refine the aerodynamic

and structural design of the missiles. Beginning in 1948, they developed a design for a modestly sized wind tunnel that could operate continuously at speeds between Mach numbers of approximately 1 and 5. To obtain this speed range, they incorporated flexible walls in the nozzle that could be recontoured to produce the specific shape needed for any Mach number within the selected range. Twenty hydraulic jacks positioned each of the top and bottom walls of the symmetric, two-dimensional nozzle. The sidewalls were flat panels that could be moved away for access to the nozzle, as well as the forward portion of the test section. The engineers wanted to be able to run the tunnel continuously over its speed range, and they looked to a JPL compressor plant for sufficient compressed air. Working with the plant engineers, they devised an unusual series-parallel connection of seven centrifugal compressors that would work. They also could use an axial-flow compressor to act as a vacuum pump that would reduce the pressure in the tunnel to simulate altitudes between 15 and 180 thousand feet.[4]

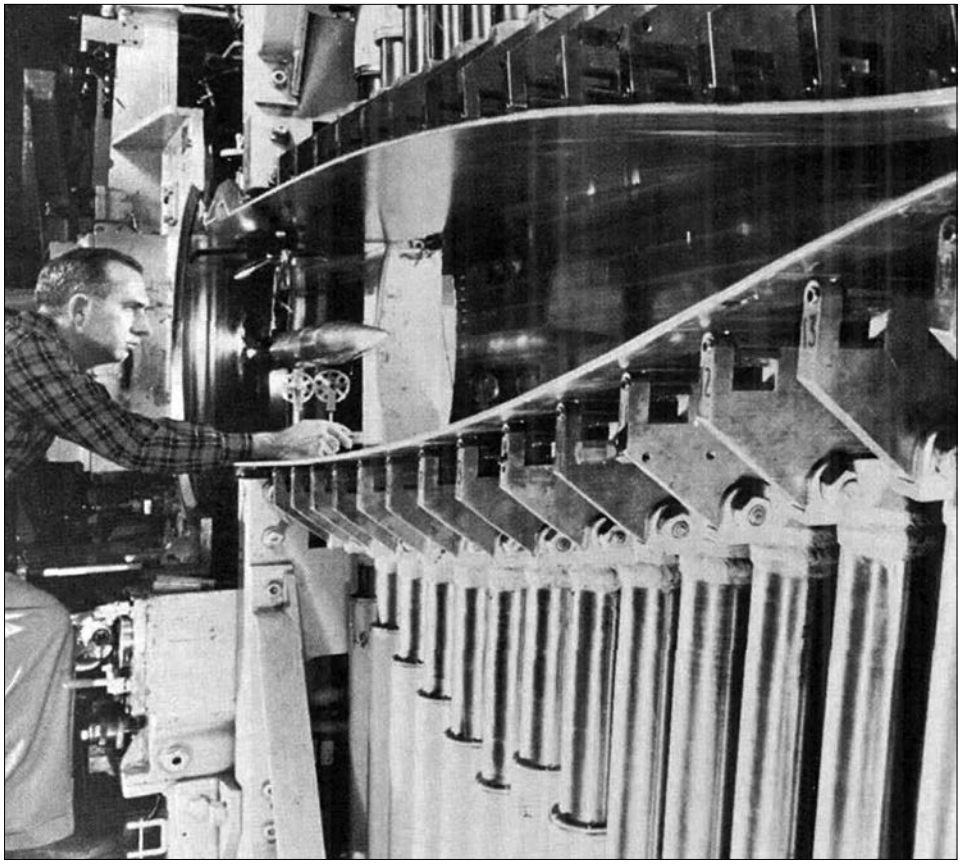
Construction of the SWT began about 1950, and the tunnel entered service in 1951. The tunnel was soon booked with test programs, so much so that a procedure had to be developed to allocate its time between the Army, Air Force, missile contractors, and those at JPL wishing to do basic aerodynamic research. After 1959, a number of programs involved tests in both the SWT and the new 21-Inch Hypersonic Wind Tunnel to take advantage of a wider range of Mach numbers. The two tunnels were similar in many respects, and their performance envelopes overlapped enough to provide essentially contiguous results from Mach 1.3 to 11. Test programs supported both military and civilian missiles and space missions.[5]

Researchers at JPL also developed equipment and techniques that enhanced the facility and their own understanding of the data measured in the SWT. These investigations included such topics as the permissible amount that a model could block the test section, using a mixed-gas atmosphere to simulate other planets, and developing a launcher and techniques for doing free-flight dynamic studies in the SWT.[6]

After JPL became a unit of NASA in 1958, its hardware role gradually shifted from rocket engines and guided missiles to the development of uncrewed spacecraft, drastically reducing its need for wind tunnels. By 1980, the laboratory needed the space the two tunnels occupied for other facilities, so NASA looked to relocate them within the agency. Robert L. Trimpi, a Langley researcher, realized that the 20-inch JPL tunnel could be useful at Langley, and he recommended that it be moved. Between 1982 and 1986, Trimpi oversaw its move and installation in Langley's Hypersonic Facilities Complex (HFC). Actually, only the core of the tunnel—its nozzle, test section, and diffuser—was moved to Virginia. Dedicated air compressors and vacuum pumps were not needed at the HFC. Langley retained its JPL name, the 20-Inch Supersonic Wind Tunnel, and it remains in service.[7]

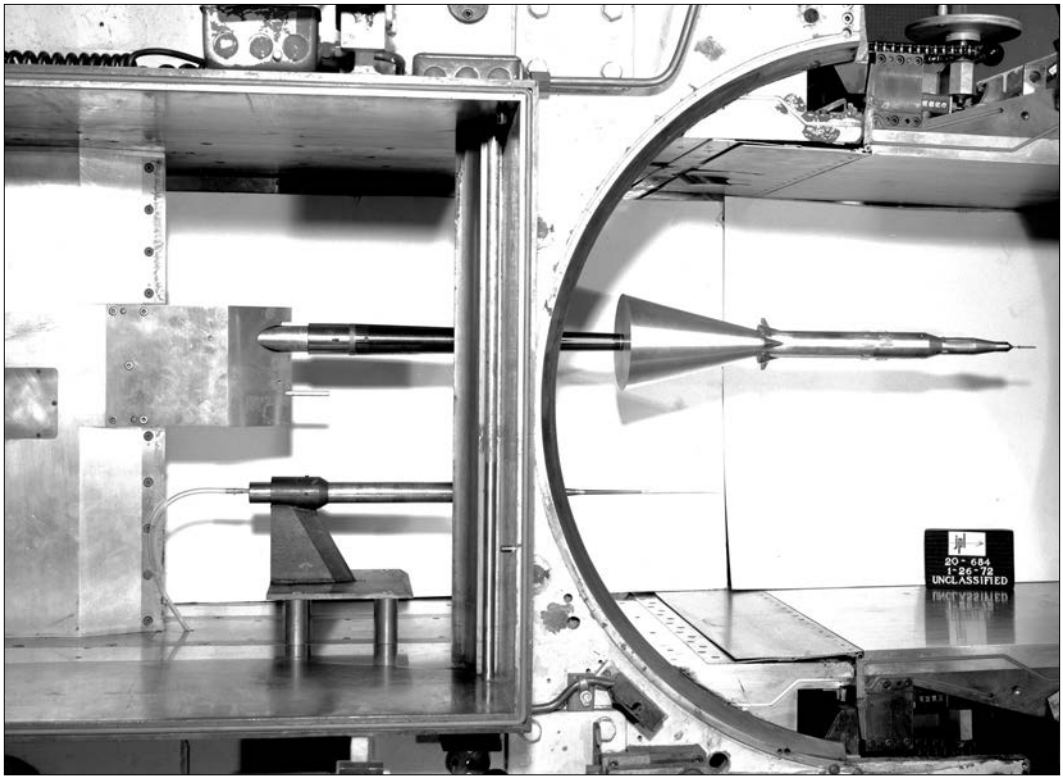


This longitudinal section drawing through the 20-Inch Supersonic Wind Tunnel's test section shows the arc support for the sting mount and its range of pitch motion. The top and bottom "flex plates" are the trailing ends of the nozzle's top and bottom walls. Flow is from right to left. (Image credit: NASA TM-33-335, Fig. 23)



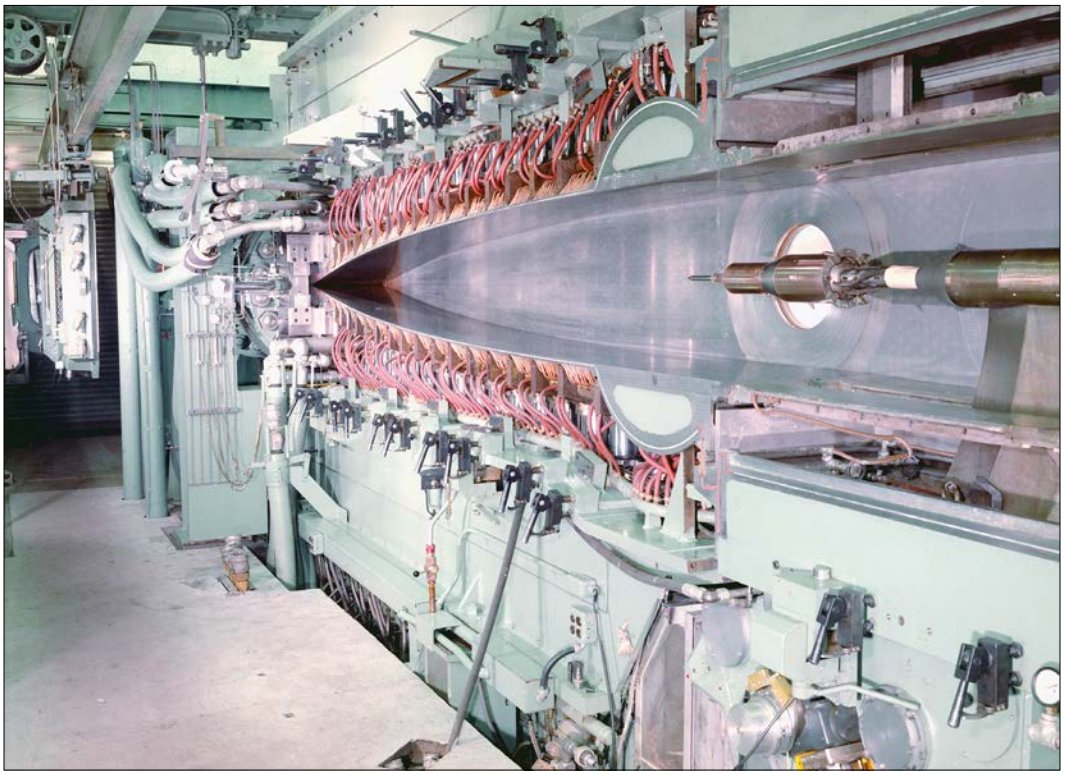
A model at a high angle of attack is visible in the 20-Inch Supersonic Wind Tunnel's test section through the open port at right. The two ports could be fitted with optically clear glass or a sidewall mounting device. (Photo credit: NASA JPL No. 34-257, Fig. 1-A2)

The 20-Inch Supersonic Wind Tunnel was controlled from this area, shown here as originally built. Much of this changed through the years as computerized data acquisition equipment came online. (Photo credit: NASA JPL No. 34-257, Fig. 1-A3)



An Apollo–Saturn V stack was sting-mounted in the 20-Inch Supersonic Wind Tunnel for a project that investigated the pressure signatures and shocks generated during launches at speeds of up to Mach 5.56. The cone simulated the exhaust plume, which generated a strong shock wave. Note the traversing pressure probe below the sting. These results were compared to those measured during the launch of Apollo 16. (Photo credit: NASA JPL/Caltech 373-6999B)

21-INCH HYPERSONIC WIND TUNNEL



The HWT's nozzle and test section, including the jack system that contoured the top and bottom walls, are visible with one side retracted. (Photo credit: NASA JPL/Caltech 373-6199-Bc)

SIGNIFICANCE

The 21-Inch Hypersonic Wind Tunnel (HWT) was the Jet Propulsion Laboratory's only conventional hypersonic wind tunnel and one of only five in NASA at the agency's birth, making it a vital resource during the early years of the nation's space program.[8] The HWT utilized flexible top and bottom walls to achieve a continuously variable range of hypersonic speeds between Mach 4 and 11. It was similar in many ways to JPL's 20-Inch Supersonic Wind Tunnel (SWT), making the HWT much like a high-speed extension of the SWT, and the same models often could be used in both tunnels during test programs.

DESCRIPTION

The HWT was a closed-circuit, hypersonic wind tunnel powered by a train of either four or six air compressors. It was constructed primarily of steel plate and structural shapes. Despite its name, the HWT's test section measured 21 inches in width only. Depending on test conditions, its height varied between 15 and 28 inches. Hypersonic nozzles must be very precisely contoured for a specific speed, and most hypersonic tunnels use nozzles with fixed contours, changing nozzle blocks to change Mach number. But JPL engineers

successfully designed a variable-contour nozzle that used a series of hydraulic jacks to flex sheets of stainless steel and, thus, recontour the nozzle for a range of speeds between Mach 4 and 11. Because of the extreme conditions at the nozzle's throat, the HWT used a pair of solid throat blocks that remained dimensionally stable at high temperature and pressure. Like the remainder of the nozzle, they were adjustable to a gap as small as 0.033 of an inch. Having the top and bottom surfaces flexible allowed both sides of the nozzle to retract for access to the nozzle and test section.[9]

Models were typically sting-mounted on an arc-type support that allowed pitch adjustment from –10 to +20 degrees and 355 degrees of rotation. Large-scale models of components, such as inlets, could be mounted to a windshield on the arc sector and enjoy the same range of pitch adjustment. The test section was fitted with two 24-inch-diameter optically clear windows for shadowgraph or schlieren photography. The HWT also featured a vertical traverse with ±15 degrees of pitch adjustment that could travel the full height of the test section. This was used primarily for wake surveys. Shadowgraph and schlieren photography equipment for flow-field visualization was available as well. Six-component, water-cooled, strain-gage balances were available for internal mounting in models, and numerous pressures and temperatures could be recorded as well. All data from the sensors were digitized, either automatically or manually, and some data processing was available using an ElectroData 202 computer system that was dedicated to the support of JPL's wind tunnels. A Digital Equipment PDP-1, the first commercial minicomputer, was later installed to furnish the primary data-processing support for the HWT and SWT.[10]

The SWT's power came in the form of compressed air from a central compressor plant that housed 11 centrifugal compressors and an axial-flow vacuum pump. For the HWT, two arrangements of compressors were normally used. For test speeds below Mach 9.5, air from the diffuser and aftercooler flowed serially through four compressors: L, H, J, and K. Air returning to the tunnel flowed through a 4,200-kilowatt electric heater that could raise the air's temperature to as high as 1,350°F to prevent liquefaction as it expanded past the nozzle's throat, and then to the settling chamber, or "supply section," as JPL engineers preferred to call it. When speeds from Mach 9.5 to the tunnel's limit of Mach 11 were needed, the compressor plant operators added two parallel-connected compressors, A and B, ahead of Compressor L for a fifth stage of compression. An axial-flow vacuum pump simulated altitudes between 85,000 and 220,000 feet by reducing the ambient pressure inside the circuit, though this was possible only below Mach 8.5. A two-stage refrigeration and activated-alumina air system at the compressor plant dried the makeup air.

Compressor L had a compression ratio of 3.8:1, followed by a 10:1 ratio for Compressor H. They were driven by 4,000- and 3,000-horsepower motors respectively. Compressors J and K each employed a 2,000-horsepower motor and delivered compression ratios of 3.4:1 and 2.7:1 respectively. Compressors A and B, which were also used with the SWT,

were each powered by a 4,000-horsepower motor, and they had a compression ratio of 2.5:1. The vacuum pump was also shared with the SWT.

The total compression ratio for the train of Compressors L, H, J, and K was over 348:1, and their drive motors totaled 11,000 horsepower. When Compressors A and B were added, 15,000 horsepower yielded a total compression ratio of 872:1.

HISTORY

During the late 1940s and into the 1950s, JPL focused on developing tactical missiles for the Army in partnership with aircraft builders, and as these projects progressed, engineers at JPL realized that they needed a wind tunnel capable of reaching speeds of Mach 4, or higher, to test and refine the aerodynamic and structural design of the missiles. They achieved this in 1951 when the SWT opened with flexible nozzle walls that gave it a speed range of Mach 1.3–5.0. The SWT worked well, but by that time leaders in the Army's missile program were interested in still-faster speeds. During 1952–53, JPL engineers developed a proposal for a 16- by 16-inch hypersonic wind tunnel with a speed range of Mach 4.5–8. While this tunnel was never built, the interest continued to grow, and by 1954 the Army had decided to fund a hypersonic tunnel at JPL.[11]

In 1954, the JPL engineers began to develop a design for such a tunnel, but the rapid increases in missile performance prompted them to consider speeds of up to approximately Mach 10. They built upon what had been successful in the SWT, including its size and the flexible top and bottom nozzle walls to provide a range of Mach numbers. This presented a daunting challenge because hypersonic nozzles must be contoured even more precisely than supersonic ones. Machining metal to a tolerance of ±1/1,000 of an inch or less was not a great challenge, so most hypersonic tunnels used one or more nozzles, each machined in a fixed contour for a specific Mach number. Speeds were changed by changing nozzles. Adjusting a sheet of stainless steel to obtain various contours that accurately was uncharted territory. Nevertheless, the engineers designed an actuator system that employed 17 hydraulic jacks to shape each of the top and bottom sides of a two-dimensional nozzle. As in the SWT, the sidewalls would be flat and retractable for access. The high temperature and pressure differentials expected across the nozzle's throat, coupled with the tiny gaps needed for hypersonic speeds, required a different throat design from that used in the SWT. The final design formed the throat out of two solid blocks that retained adequate dimensional stability under the calculated range of conditions. A heavy-duty adjustment system moved the blocks vertically to set and maintain the gap between them to as small as 0.033 of an inch, ±0.001 of an inch.[12]

The nozzle parameters were governed in part by a desire to build a tunnel about the same size as the SWT, which had an 18- by 20-inch test section. Trading off the many design parameters involved, the engineers arrived at a test section that measured 21 inches wide with a nominal height of 21 inches, although the actual height would vary between 15 and 28 inches depending on individual test conditions. As in the SWT, the flexible walls of the nozzle ended at the test section, and the test section had to match

the nozzle height for any given speed, which had by then been determined to be Mach 4–11. The Mach 4–5 range would overlap the upper portion of the SWT's range and allow direct comparisons and calibration between the two tunnels.[13]

The engineers again enlisted the help of JPL plant engineers to design a compressor arrangement that could furnish the HWT with adequate compressed air, but they wanted it available for continuous operation—a feat not yet achieved in a hypersonic tunnel. No single configuration would work, but they devised two configurations that would. Below Mach 9.5, the necessary rate of flow with compression ratio of almost 350:1 could be obtained by connecting four compressors, labeled L, H, J, and K, in series. Above Mach 9.5, the parallel set of Compressors A and B could be connected ahead of Compressor L to obtain the whopping 870:1 compression ratio needed. The vacuum pump used with the SWT could serve the HWT as well, but the main compressors' capabilities limited its use to speeds below Mach 8.5.[14]

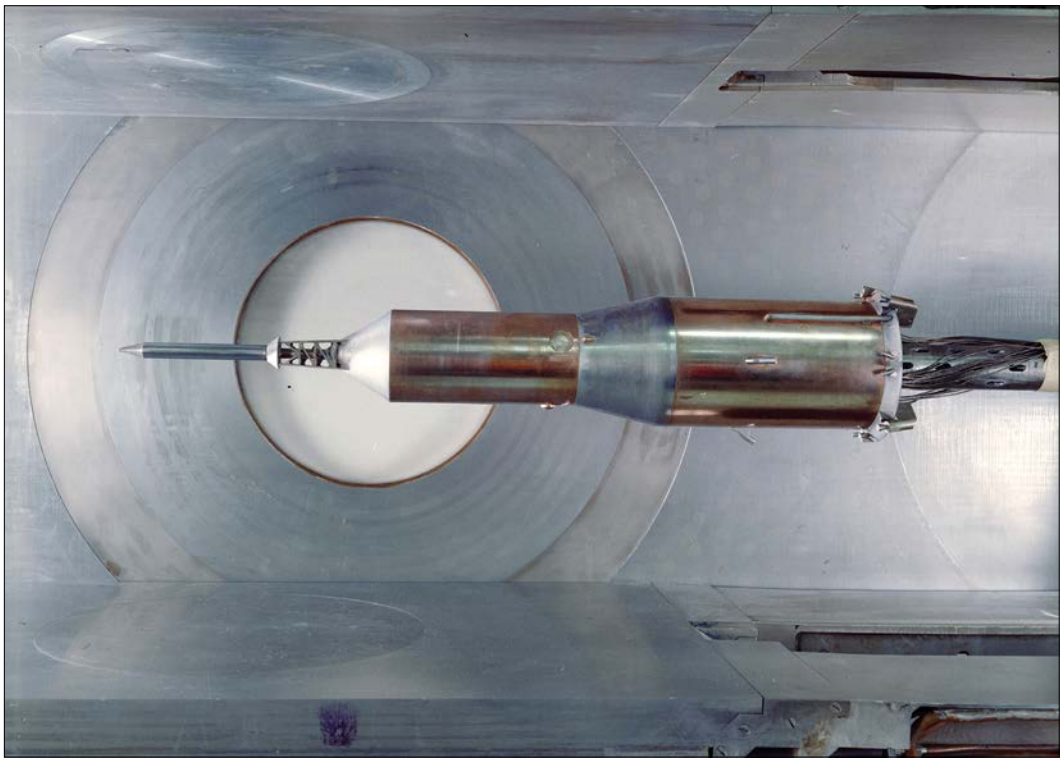
Hypersonic tunnels require air to be heated prior to its passage through the nozzle. The expansion ratio between the throat and test section is so large that air will cool to the point that it begins to change from a gas to a liquid. This is not condensing water vapor, but the air itself, and it not only renders aerodynamic results invalid, but often damages the test object as well. Preventing it requires heating the incoming air to temperatures that often exceed 1,000°F. The design team installed a 4,200-kilowatt electric heater ahead of the supply section that could heat the air to temperatures that ranged between 100 and 1,350°F. The air regains much of this heat as it decelerates through the diffuser, so the team installed a water-cooled aftercooler after the diffuser to remove most of it. The cooler air substantially improved the efficiency of the compressors.[15]

Construction of the HWT began about 1955, and the tunnel entered service in 1957 or 1958.[16] It was soon booked with test programs, so much so that a procedure had to be developed to allocate its time between the Army, Air Force, missile contractors, and those at JPL wishing to do basic aerodynamic research. A number of programs involved tests in both the SWT and the new 21-Inch Hypersonic Wind Tunnel to take advantage of a wider range of Mach numbers. The two tunnels were similar in many respects, and their performance envelopes overlapped enough to provide essentially contiguous results from Mach 1.3 to 11. Test programs supported both military and civilian missiles and space missions.[17]

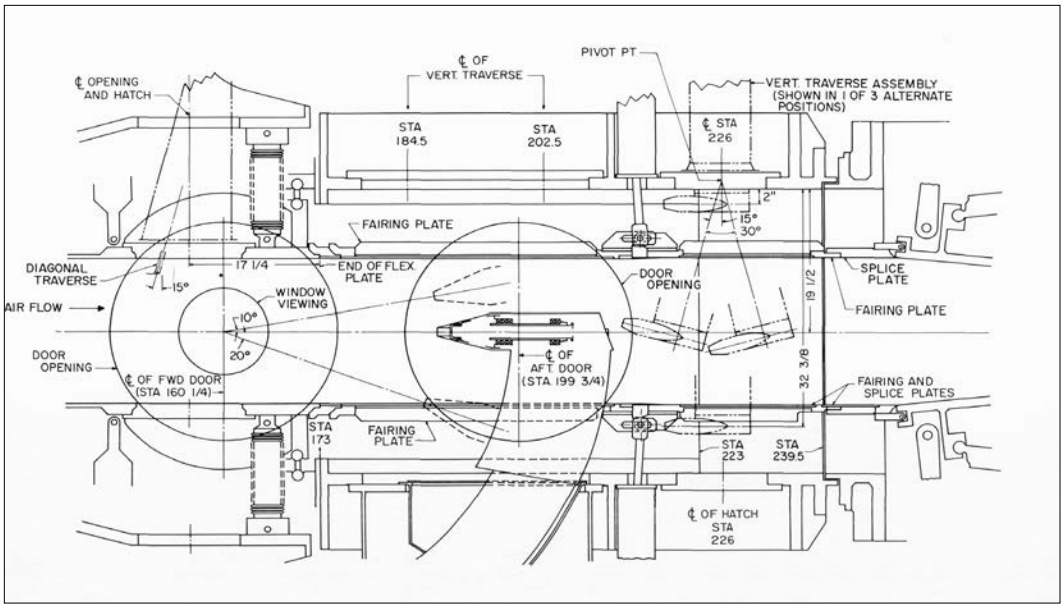
Researchers at JPL also developed techniques that enhanced their use of the HWT. These included free-flight telemetry techniques, an evaluation of calorimetric models as tools to determine aerodynamic heating rates, and studies of flow fields close to bodies at speeds of up to Mach 6.5.[18]

After JPL became a unit of NASA in 1958, its hardware role gradually shifted from rocket engines and guided missiles to the development of uncrewed spacecraft, drastically reducing its need for wind tunnels, and the HWT was placed in standby status in 1975. The emergence of the National Aerospace Plane (NASP) program in 1987 generated interest in reactivating it, but JPL elected not to do so. The laboratory needed the space

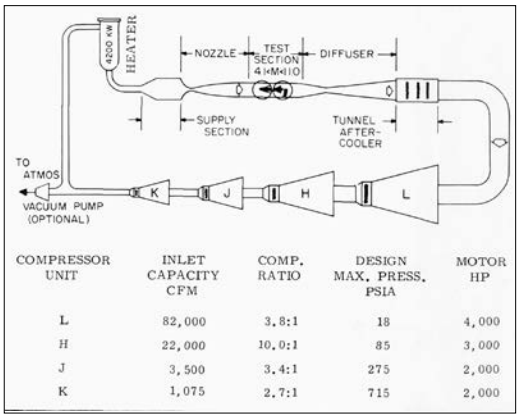
it occupied for other facilities, so NASA looked to relocate it within the agency. The Lewis Laboratory in Cleveland, Ohio, prepared a proposal to re-erect the HWT. NASA approved disassembly and shipment of the HWT, including its compressors, to Lewis's Plum Brook Station in Sandusky, Ohio, in 1988. Though Lewis engineers selected a site and did most of the engineering necessary to re-erect the HWT, funding for the project never materialized, and the components remained in storage at Plum Brook. They were finally sold to a salvage dealer in 2007, and no portion of the HWT is known to survive.[19]



This Nike-Iroquois was just one of the missile and spacecraft models tested in the 21-Inch Hypersonic Wind Tunnel. (Photo credit: NASA JPL/Caltech 373-6200-Bc)

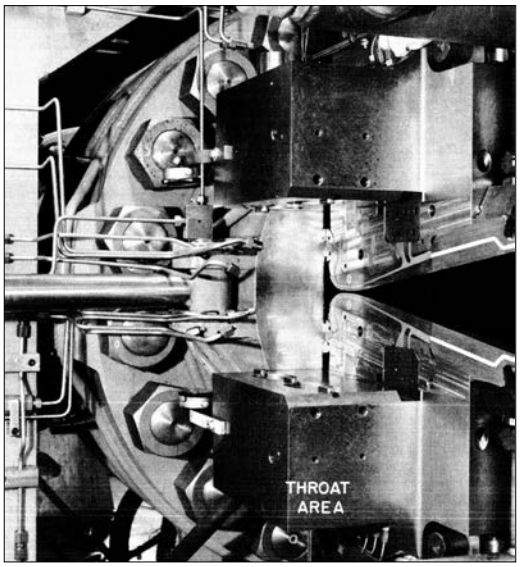


This longitudinal section drawing of the 21-Inch Hypersonic Wind Tunnel's test section shows the arc support for the sting mount and its range of pitch motion, as well as the vertical and diagonal traverses. (Image credit: NASA CR-51851, Fig. 4-2)

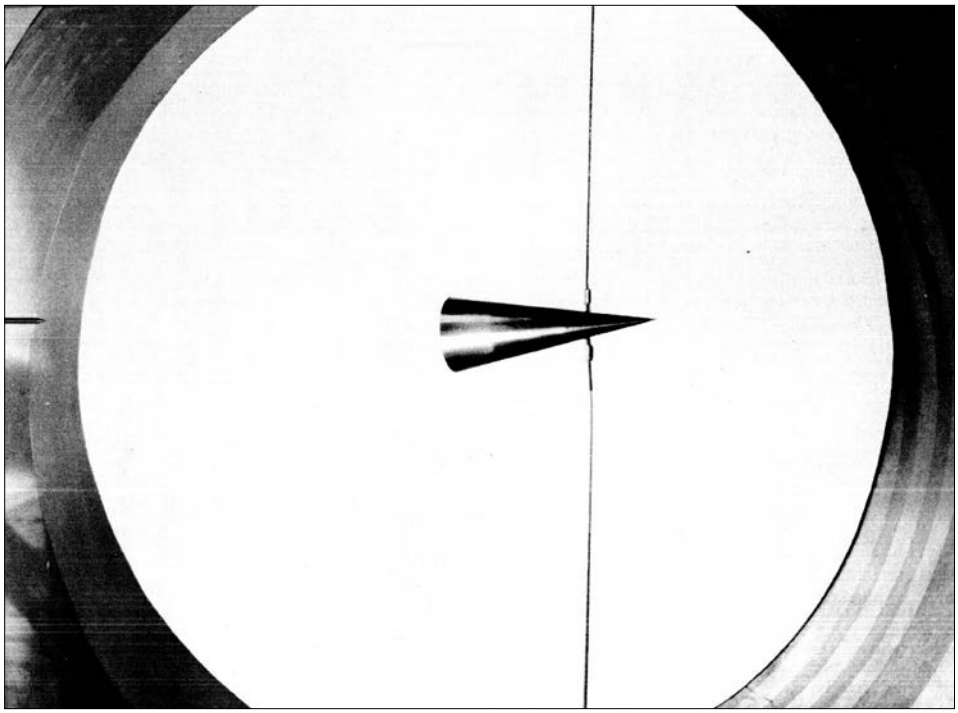


COMPRESSOR UNIT	INLET CAPACITY CFM	COMP. RATIO	DESIGN MAX. PRESS. PSIA	MOTOR HP
L	82,000	3.8:1	18	4,000
H	22,000	10.0:1	85	3,000
J	3,500	3.4:1	275	2,000
K	1,075	2.7:1	715	2,000

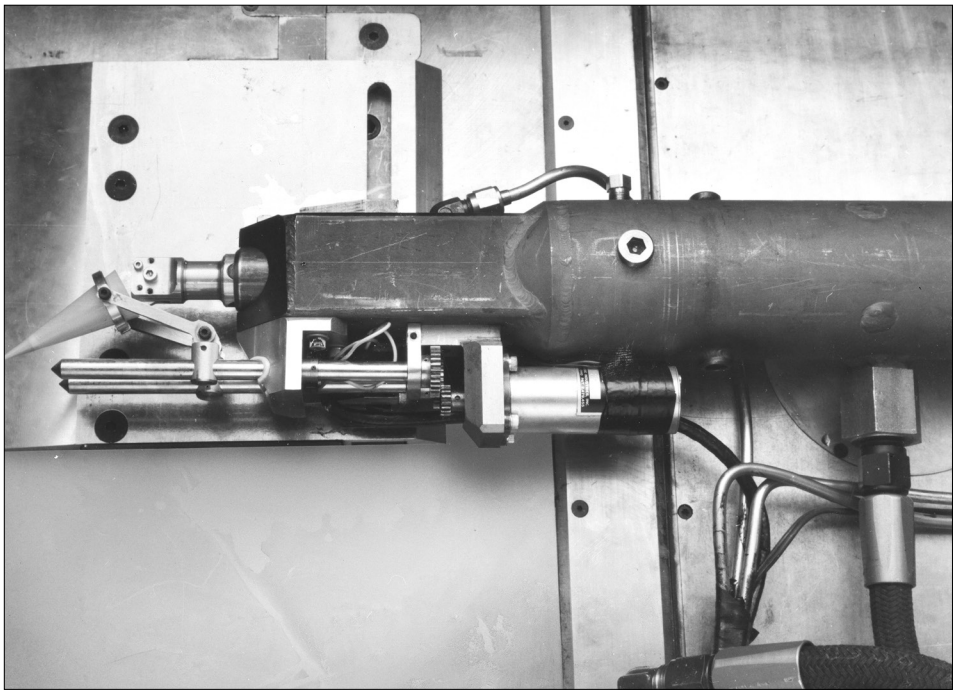
This schematic drawing shows the Hypersonic Wind Tunnel and its supporting compressors. Note the second throat in the diffuser to control the decelerating shock. Compressors L, H, J, and K were sufficient for speeds below Mach 9.5, but Compressors A and B were connected as a fifth stage between Mach 9.5 and 11. The heater prevented air liquefaction in the nozzle. (Image credit: NASA CR-51851, Fig. B-1)



The detail view shows the solid blocks and positioning system at the nozzle's throat, needed to accurately maintain the small gap under changing temperature and pressure conditions. (Photo credit: NASA TM-33-335, Fig. 2a)



Two methods for attempting free-flight test conditions in the 21-Inch Hypersonic Wind Tunnel are shown here: wire suspension (top) and a pneumatic launching gun (bottom). Similar cones were used as test models with both systems. The pneumatically launched cones flew free for a short distance until stopped by the airflow, after which they were blown along the floor into a catch basket (not shown). They carried small radio pressure transmitters to transmit data to a receiver. (Photo credits: Top: NASA TM-33-335, Fig. 32; Bottom: NASA JPL/Caltech 373-6604)



ENDNOTES

1 GALCIT was an acronym for Guggenheim Aeronautical Laboratory, California Institute of Technology.

2 Except as noted, description and performance information is from George G. Goranson and Robert E. Covey, "Wind Tunnel Facilities at the Jet Propulsion Laboratory," *Technical Release 34-257* (Pasadena, CA: NASA JPL, 1961, Rev. 1962) and E. A. Laumann, "Jet Propulsion Laboratory Wind Tunnel Facilities," *Technical Memorandum 33-335* (Pasadena, CA: NASA JPL, 1967).

3 "Proposal for Procurement of a High-Speed Digital Computer," 20 Aug. 1957, California Institute of Technology Archives, JPL Collection, Folder 14.16.

4 "AAAC Research Facilities," *AAAC Annual Report, FY 2002–2003* (Hampton, VA: NASA LaRC, Aerodynamics, Aerothermodynamics and Acoustics Competency, 2003), p. 123. Also author's inspection of the nozzle and test section at NASA LaRC. Also Laumann, *Technical Memorandum 33-335*, p. 1.

5 Reports of typical tests include H. Carl Thorman, "Alleviation of Aerodynamically Induced Vibration in the Sergeant Missile," *Report 20-124* (Pasadena, CA: NASA JPL, 1959); Maurice J. Argoud, "Test of the Space-General Nike-Iroquois Model in the JPL 20-Inch Supersonic Wind Tunnel," *Report WT 20-576* (Pasadena, CA: NASA JPL, 1964); John J. Minich, "Captive Dynamic-Stability Tests of the Gemini Abort-Seat Configuration in the JPL 20-Inch Supersonic Wind Tunnel," *Report WT 20-583* (Pasadena, CA: NASA JPL, 1964); and Raymond M. Hicks, Joel P. Mendoza, and Charles L. Thomas, "Pressure Signatures for the Apollo Command Module and the Saturn V Launch Vehicle with a Discussion of Strong Shock Extrapolation Procedures," *Technical Memorandum X-62117* (Washington, DC: NASA, 1972).

6 Bain Dayman, Jr., "Prediction of Blocking in the Supersonic Wind Tunnel During an Attempted Start," *External Publication No. 669* (Pasadena, CA: NASA JPL, 1959); Howard Koester, Gilbert Herrera, and Donald Hanks, "The Use of a Conventional Wind Tunnel as a Multigas Facility," *Technical Memorandum 33-145* (Pasadena, CA: NASA JPL, 1963); and H. P. Holway, J. G. Herrera, and B. Dayman, Jr., "A Pneumatic Model Launcher for Free-Flight Testing in a Conventional Wind Tunnel," Technical Memorandum 33-177 (Pasadena, CA: NASA JPL, 1964).

7 J. L. Dillon, R. L. Trimpi, and A. E. Schwartz, "The Langley 20-Inch Supersonic Wind Tunnel," *Paper No. 86-0765-CP* (Reston, VA: AIAA, 1986).

8 On 1 October 1958, NASA's conventional hypersonic wind tunnels were this one and four at Langley: the 11-Inch Hypersonic Tunnel, the 20-Inch Mach 6 Tunnel, the 37-Inch Mach 10 Helium Tunnel, and the 60-Inch Mach 18 Helium Tunnel. A few others were in the planning phase or under construction.

9 Except as noted, description and performance information is from George G. Goranson and Robert E. Covey, "Wind Tunnel Facilities at the Jet Propulsion Laboratory," *Technical Release 34-257* (Pasadena, CA: NASA JPL, 1961, Rev. 1962) and Laumann, *Technical Memorandum 33-335*.

10 "Proposal for Procurement of a High-Speed Digital Computer," 20 Aug. 1957, California Institute of Technology Archives, JPL Collection, Folder 14.16.

11 Louis G. Dunn, JPL Director, "Proposal 20-4: Proposed 1953 ORDCIT Project Research Program on Jet Propulsion Systems, Guided Missile Test Vehicles, and Related Subjects for the Department of the Army, Ordnance Corps," 2 Sept. 1952 (Rev. 31 Oct. 1952) and "Proposal for the Design and Construction of a 16 × 16 Inch Hypersonic Wind Tunnel at the Jet Propulsion Laboratory, 29 June 1953, California Institute of Technology Archives, JPL Collection, Folder 14.5.

12 The development of this nozzle design is detailed in H. N. Riise, "Flexible-Plate Nozzle Design for a Two-Dimensional Supersonic Wind Tunnels," *Report 20-74* (Pasadena, CA: JPL, 1954); and H. M. Schurmeier, "Design and Operation of a Continuous-Flow Hypersonic Wind Tunnel Using a Two-Dimensional Nozzle," *AGARDograph 38* (Paris: NATO Advisory Group for Aerospace Research and Development, 1959).

13 Goranson and Covey, *Technical Release 34-257*, p. A-1.

14 Laumann, *Technical Memorandum 33-335*, p. 5.

15 Ibid., p. 1.

16 There are unresolved discrepancies regarding the HWT's completion date, from 1954 (Donald D. Baals and William R. Corliss, *Wind Tunnels of NASA*) to 1959 (caption for NASA photograph GPN-2003-00065, "JPL's Hypersonic Wind Tunnel"). Considering the Dunn proposal (note 3), a project *start* date of 1954 is plausible, which would make a completion date any time between 1956 and 1959 reasonable. The publication dates of the Riise and Schurmeier papers (note 4) support this as well, as do claims by Baals and Corliss and others that the HWT was operating when NASA began on 1 Oct. 1958. Accordingly, the late-1957 to early-1958 period appears to be the most likely one for the 21-Inch Hypersonic Wind Tunnel's completion.

17 Reports of typical tests include Robert W. Weaver, "Test of the NAA X-15 Model in the JPL 21-Inch Hypersonic Wind Tunnel," *Report WT 21-128* (Pasadena, CA: NASA JPL, 1963); Maurice J. Argoud, "Test of the Space-General Nike-Iroquois in the JPL 21-Inch Hypersonic Wind Tunnel," *Report WT 21-145* (Pasadena, CA: NASA JPL, 1964); and Robert W. Weaver, "Test of a NASA Blunt Body with Flares in the JPL 20-Inch Supersonic and 21-Inch Hypersonic Wind Tunnels," *Report WT 21-115* (Pasadena, CA: NASA JPL, 1963).

18 John J. Welton, "Free-Flight Telemetry Testing in the Jet Propulsion Laboratory Wind Tunnels," *Technical Report 32-775* (Pasadena, CA: NASA JPL, 1965); E. A. Laumann, "Determining Aerodynamic Heating Rates Using Calorimetric Models in the Jet Propulsion Laboratory Hypersonic Wind Tunnel," *Technical Memorandum 33-121* (Pasadena, CA: NASA JPL, 1963); and Robin B. Blaylock, "Pressure Test of Several Models in Air-Carbon-Dioxide Mixtures in the 21-Inch Hypersonic Wind Tunnel," *Report WT 21-141* (Pasadena, CA: NASA JPL, 1964).

19 Jeffrey E. Haas, Roger Chamberlin, and John H. Dicus, "New Hypersonic Facility Capability at NASA Lewis Research Center," *Technical Memorandum 102028* (Washington, DC: NASA, 1989), pp. 3–4. Also Robert S. Arrighi, conversation with author, 9 Feb. 2008.

ACRONYMS

ABMA	Army Ballistic Missile Agency
AC	alternating current
AERL	Aircraft Engine Research Laboratory
AES	Atmospheric Entry Simulator
AFDD	Aeroflightdynamics Directorate
AFE	Aero-assist Flight Experiment
AHSTF	Arc-Heated Scramjet Test Facility
AIAA	American Institute of Aeronautics and Astronautics
AMB	Analytical Methods Branch
ARC	Ames Research Center
ARES	Aeroelastic Rotor Experimental System
ASME	American Society of Mechanical Engineers
ATP	advanced turboprop
ATT	Annular Transonic Tunnel
AWT	Altitude Wind Tunnel
AWT	Atmospheric Wind Tunnel
BART	Basic Aerodynamics Research Tunnel
BLTT	Boundary Layer Transition Tunnel
BWT	Bisonic Wind Tunnel
CAA	Civil Aeronautics Administration

CADDE	Central Automatic Digital Data Encoder
CAEB	Central Air Equipment Building
CFD	computational fluid dynamics
CFHT	Continuous-Flow Hypersonic Tunnel
CHSTF	Combustion-Heated Scramjet Test Facility
CMAPS	compact multimission aircraft propulsion simulator
CPS	Central Process System
DAMPR	Digital Automatic Multiple Pressure Recorder
DC	direct current
DCSCTF	Direct-Connect Supersonic Combustion Test Facility
DrIFT	Droplet Imaging Flow Tunnel
EAST	Electric Arc Shock Tube
EPRB	Engine Propeller Research Building
ERA	Engineering Research Associates
ERB	Engine Research Building
ERT	Engine Research Tunnel
ESP	electronically scanned pressure
ET	Expansion Tube
FDRF	Flight Dynamics Research Facility
FFT	Free-Flight Tunnel
FSD	Full-Scale Division
FST	Full-Scale Tunnel
GALCIT	Guggenheim Aeronautical Laboratory, California Institute of Technology
GASL	General Applied Science Laboratories
GDL	Gas Dynamics Laboratory
GMDD	Guided Missile Development Division
GRC	Glenn Research Center
HAPB	Hypersonic Air-Breathing Propulsion Branch
HARF	Hypersonics and Applied Research Facility
HFA	Hypersonic Flow Apparatus
HFC	Hypersonic Facilities Complex
HFFAF	Hypervelocity Free-Flight Aerodynamic Facility
HFFF	Hypervelocity Free-Flight Facility
HFFGDF	Hypervelocity Free-Flight Gun Development Facility
HFFRF	Hypervelocity Free-Flight Radiation Facility
HGRS	heavy gas reclamation system
HHeT	Hypersonic Helium Tunnel
HHTF	Hydrogen Heat Transfer Facility
HLFC	hybrid laminar flow control
HRC1	High Reynolds Number Channel Number 1
HRC2	High Reynolds Number Channel Number 2

HRE	Hypersonic Research Engine
HRF	High Reynolds Number Facility
HRWT	High Reynolds Wind Tunnel
HST	High-Speed Tunnel
HSWT	High-Speed Wind Tunnel
HTF	Hypersonic Tunnel Facility
HTT	Heat Transfer Tunnel
HTT	High-Temperature Tunnel
HWT	Hypersonic Wind Tunnel
HYPULSE	Hypersonic Pulse
HYST	Hypersonic Tunnel
IPFL	Icing Physics Flow Laboratory
IRD	Instrument Research Division
IRT	Icing Research Tunnel
ISTAR	Integrated System Test of an Airbreathing Rocket
JPL	Jet Propulsion Laboratory
LAL	Langley Aeronautical Laboratory
LaRC	Langley Research Center
LCI	load commutated inverter
LDST	Low Density Shock Tube
LDV	laser Doppler velocimetry
LeRC	Lewis Research Center
LFC	laminar flow control
LFPL	Lewis Flight Propulsion Laboratory
LFST	Langley Full-Scale Tunnel
LHI	laser holographic interferometer
LMAL	Langley Memorial Aeronautical Laboratory
LOX	liquid oxygen
LPT	low-pressure turbine
LST	Low-Speed Tunnel
LSWT	Low-Speed Wind Tunnel
LTPT	Low-Turbulence Pressure Tunnel
LTT	Low-Turbulence Tunnel
LUPA	Lewis Unitary Plan Act
LV	laser velocimetry
M4BDF	Mach 4 Blowdown Facility
M50HeT	Mach-50 Helium Tunnel
MASTIF	Multiple Axis Space Test Inertia Facility
MISS	Model Integrated Support System
MIT	Massachusetts Institute of Technology
mph	miles per hour

MPSS	Model Protection and Shut-down System
MSFC	Marshall Space Flight Center
MVD	mean volumetric diameter
NACA	National Advisory Committee for Aeronautics
NASP	National Aero-Space Plane
NFAC	National Full-Scale Aerodynamics Complex
NPL	National Physical Laboratory
NTF	National Transonic Facility
PARD	Pilotless Aircraft Research Division
PBR	Pressurized Ballistic Range
PDM	Pittsburgh–Des Moines Steel Company
PES	Parabolic Entry Simulator
PIV	particle-imaging velocimetry
PMET	Pilot Model Expansion Tube
PRT	Propeller Research Tunnel
PSCL	Propulsion Simulator Calibration Laboratory
psi	pounds per square inch
psia	pounds per square inch absolute
PSL	Propulsion Systems Laboratory
PT	Pressure Tunnel
PWA	Public Works Administration
PWT	Pressure Wind Tunnel
QueSST	Quiet Supersonic Technology
RSV	radiation shutter valve
S/SWTF	Supersonic/Subsonic Wind Tunnel Facility
SAIC	Science Applications International Corporation
SCAT	Supersonic Commercial Air Transport
SFFWT	Supersonic Free-Flight Wind Tunnel
SLS	Space Launch System
SPC	Space Power Chambers
SPF	Space Power Facility
SPT	Supersonic Pressure Tunnel
SRB	solid rocket booster
SST	supersonic transport
SSTs	Small Supersonic Tunnels
ST	Spin Tunnel
ST	Supersonic Tunnel
STC	Scramjet Test Complex
SWT	Supersonic Wind Tunnel
TBT	Transonic Blowdown Tunnel
TCT	Transonic Cryogenic Tunnel

TDT	Transonic Dynamics Tunnel
TFC	Transonic Flutter Cascade
TPS	Turbine Powered Engine Simulators
TPT	Transonic Pressure Tunnel
TST	Thermal Structures Tunnel
TT	Transonic Tunnel
TTBC	Transonic Turbine Blade Cascade Test Facility
TWT	Trisonic Wind Tunnel
UPWT	Unitary Plan Wind Tunnel
USAAF	United States Army Air Forces
V/STOL	vertical/short take-off and landing
VDT	Variable-Density Tunnel
VFS	Vibration and Flutter Section
VIST	Vertical Icing Studies Tunnel
VST	Variable Supersonic Tunnel
VST	Vertical Spin Tunnel
VWT	Vertical Wind Tunnel

ABOUT THE AUTHORS

J. Lawrence Lee

J. Lawrence "Larry" Lee was born in Albany, New York, in 1948, but he grew up primarily in the American South and Southwest, graduating from high school in Dallas, Texas, and doing two years of undergraduate study at East Texas State University. After transferring to Auburn University, he earned a bachelor of mechanical engineering and received the Old Guard Prize from the American Society of Mechanical Engineers (ASME) in 1971. Lee then practiced engineering with transportation, manufacturing, and engineering consulting companies for more than 20 years and held Professional Engineering registrations in three states.

After over two decades of engineering practice, Lee decided to refocus his career on the history and development of engineering and technology. He returned to Auburn University for graduate study, earning a master of arts in 1995 and a doctor of philosophy in 2001, with a major in the history of technology under James R. Hansen. In 2004, he joined the Historic American Engineering Record, part of the National Park Service's Cultural Resources Program, as Engineer-Historian, specializing in transportation, power systems, technological evolution, and the nature of engineering thought and practice.

This is Lee's first book for NASA, but he was a contributor to NASA's documentary history of aerodynamics multivolume work *The Wind and Beyond*, edited by James R. Hansen. Additionally, he has written over two dozen papers and articles dealing with the technology and history of railroads, control systems, aerospace hardware, marine vessels, and engineering education. He has been a member of the editorial advisory panel for the Institution of Civil Engineers' *Engineering History and Heritage*.

Lee is a fellow of the ASME and served three terms as chair of the society's Committee on History and Heritage, as well as having served in other section, region, and public information board offices. Outside of work, he particularly enjoys model railroading, rail history, clarinet, and a vintage Jaguar automobile. Lee and his wife Judy make their home in Sterling, Virginia. The couple has one married daughter, one granddaughter, and a spoiled cocker spaniel.

Robert Arrighi

Robert S. Arrighi has supported the History Program at NASA's Glenn Research Center for over 20 years. In this role, he has documented the history of the center through a number of books, articles, and websites; managed the center's archival collection; and provided research and reference support.

The Cleveland-area native received his bachelor of arts in history from Cleveland State University and a master of library and information science from Kent State University. He began his career as a project archivist with Virginia Dawson and Mark Bowles at History Enterprises, Inc., which led to his association with NASA Glenn during the documentation of the Plum Brook Reactor Facility.

At Glenn, Arrighi has helped the center meet its historical mitigation obligations prior to the demolition of a several significant, but out-of-date test facilities. These projects have resulted in books, documentaries, websites, and Historic American Engineering Reports that preserve the legacy of the lost facilities.

In 2011, center management asked him to author a new center history for Glenn's 75th anniversary. The resulting *Bringing the Future Within Reach—Celebrating 75 Years of the NASA John H. Glenn Research Center* was published in 2016.

In recent years, Arrighi has been writing articles and creating web pages highlighting specific events and people in the center's history and has contributed to the establishment of the Glenn Hall of Fame.

Arrighi has received a number of NASA group achievement awards and in 2013 received NASA's Exceptional Public Service Medal for exceptional achievement in documenting, preserving, and promoting the rich history of NASA, its mission, and its valuable historical cultural resources. He was the recipient of the 2010 NASA History Program Annual History Award.

He and his wife Sarah live in Brecksville, Ohio.

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