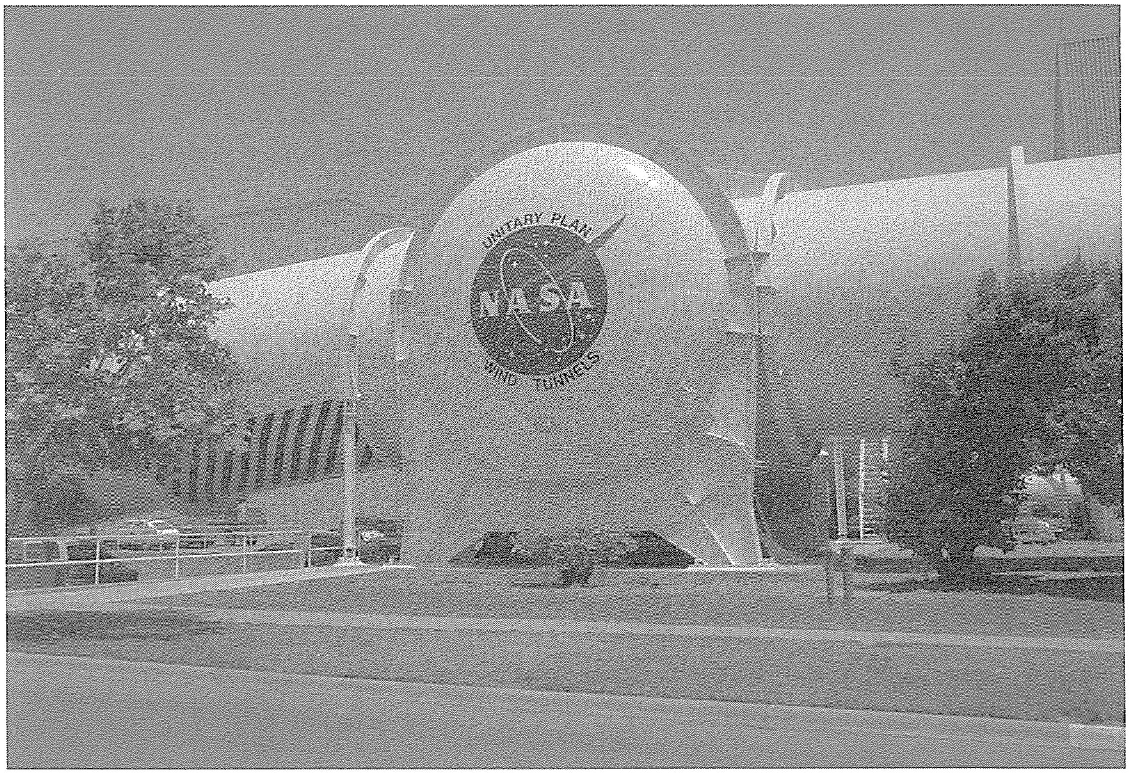
An ASME International Historic
Mechanical Engineering Landmark

Unitary Plan Wind Tunnel



NASA Ames Research Center • Moffett Field, California • May 10, 1996

The American Society of Mechanical Engineers

Cover Photo: *Flow diversion valve painted with the National Aeronautics and Space Administration's symbol fondly known as "The Meatball."*

The Beginning

The discovery of Germany's advanced wind tunnel facilities after World War II, in conjunction with its leadership in the research and development of rocket engines, jet engines and supersonic guided missiles posed a serious challenge to America's national security. Following the war, the United States found its fund of basic aeronautical research seriously depleted. The nature and scope of Germany's research and development work indicated what the future could hold in new aeronautical developments.

America's existing wind tunnel facilities were not up to meeting the challenge that supersonic aircraft and missile research demanded. In 1945, Bruce Ayer of the National Advisory Committee on Aeronautics' (NACA) Engine Research Laboratory in Cleveland, Ohio underscored this concern. In writing to NACA Chairman George Lewis he stated that the Committee's facilities were "woefully inadequate" for the supersonic research of the future and he recommended an "Altitude and Supersonic Research Laboratory" be constructed.

Spurred by this recommendation, both NACA and the U.S. Armed Services assessed the state of America's aeronautical research facilities. They recognized independently that new facilities would be required in order to capitalize on the potentials of supersonic flight. In an April 1946 meeting of NACA, which included the military, the separate proposals to address the problem were put on the table.

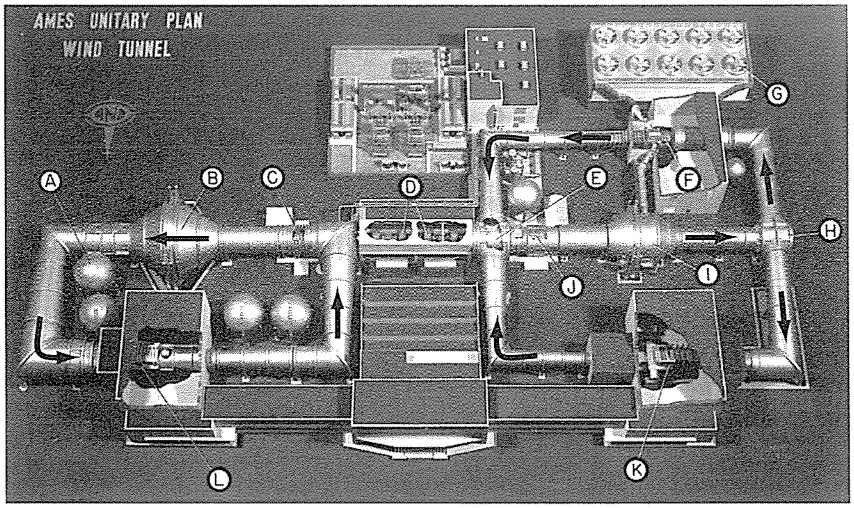
It was agreed that a "unitary plan" addressing the combined aeronautical research needs of all the agencies involved was the best approach. A Special Panel on Supersonic Laboratory facilities was formed, headed by NACA member Arthur E. Raymond. This group which came to be known as the Raymond Panel, included representatives from the Army, the Navy, the aircraft industry, the aircraft engine companies and the NACA.

In June 1946, the Raymond Panel submitted to NACA a coordinated wind tunnel program which included all the requirements proposed by the individual agencies at work on the problem. The National Advisory Committee on Aeronautics concluded further study was required and set up a Special Committee on Supersonic Facilities headed by Dr. Jerome C. Hunsaker.

Completing its work in January 1947, the Hunsaker Committee proposed a unitary plan for wind tunnel facilities that would serve the combined needs of military and civil aviation. This plan was forwarded to the Joint Research and Development Board who reduced the scope of the plan, approving only the most urgently needed facilities for construction.

In 1949, NACA asked and obtained Budget Bureau authorization to submit the proposed Unitary Plan legislation to the 81st Congress. The House and Senate passed a Joint Bill on October 19 and it was signed into law by President Harry Truman on October 27, 1949. Under Title I, the Unitary Wind Tunnel Plan Act of 1949 authorized $136 million for NACA to construct "transonic and supersonic wind tunnels of a size, design and character adequate for the efficient conduct of experimental work in support of long-range fundamental research within the continental United States."

Final approval of the program came from Congress on June 29, 1950, authorizing only $75 million, approximately one-half of that originally appropriated under Title I of the 1949 Act.



A. Dry Air Storage Spheres
B. Aftercooler
C. 3-Stage 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

National Aeronautics and Space Administration
Ames Research Center, Moffett Field, California

Design and Construction

In December, 1949, NACA Director Dr. Hugh L. Dryden established a project Office for the Unitary Wind Tunnel Programs to supervise and direct the design, engineering, and construction of the authorized NACA wind tunnel facilities. John F. Parsons was appointed Chief of the Project, which was located at Ames Aeronautical Laboratory, Moffett Field, California.

In March, 1950, the NACA Director instructed each of the three NACA Laboratories to establish a Unitary Plan Design Group. Ralph H. Huntsberger was named the head of the Ames design group.

The design team was composed of many of NACA's and industry's most skilled engineers. Ames' Paul Radich was responsible for the diversion valves, Adrien Anderson for the design of the 11-stage compressor, and Norman Martin for the design of the 3-stage compressor. In addition, from General Electric, Mal Horton was responsible for the design of the drive motors and control system and Veeder Nellis for the design of the motor disconnect couplings.

Design work on the Ames Unitary Plan wind tunnel began in late 1949 and it was soon apparent that the 8-foot by 8-foot test section, capable of Mach 0.7 to 3.5, was impractical. The designers later discovered, within their limited budget, they could achieve their objectives with three tunnels. The redesign consisted of three test sections, one transonic and two supersonic, powered by a single drive system of 180,000 horsepower continuous and covering a Mach number range of 0.3 to 3.5.

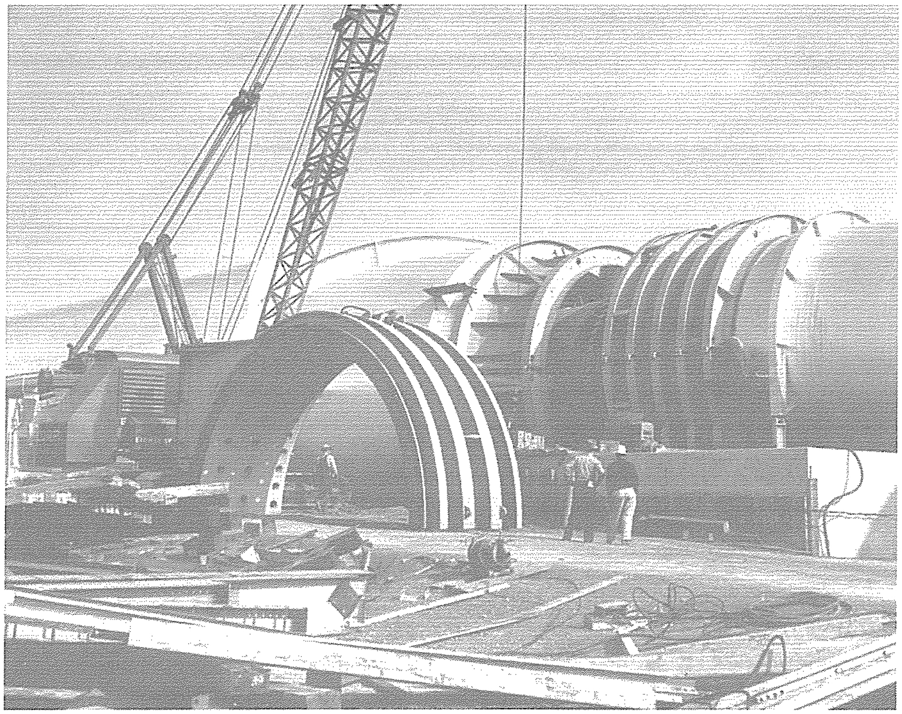
The Ames Unitary Plan Wind Tunnel (UPWT) was the largest, most complex supersonic wind tunnel facility within NACA and the arrangement of three test sections powered by a common set of motors is unique. The tunnel shell, made of welded steel plates, was constructed by the Chicago Bridge and Iron and the American Bridge and Iron Companies.

Four General Electric intercoupled motors power either an eleven-stage or a three-stage axial flow compressor manufactured by the Newport News Company of Virginia. The drive motors were the largest wound-rotor induction machines of their time and were installed in a tandemly coupled arrangement between the two compressors.

The entire drive train, including the compressors, was to be supported by a single foundation, and hence, the designers arranged it in the shape of a catenary, in the elevation, to reduce the bending stress in the shaft. The requirement for good flow quality drove machining tolerances and finishes to extremes. Decisions regarding tradeoffs between absolute flow quality and budget realities were constantly being made. Often the engineers turned to modeling features of the tunnel to resolve these and other technical issues.

Beyond design and budget challenges, were those in relation to the power available to run the facility, the availability of manufacturing facilities to build the components, and adequate transportation to bring the components to the site. In 1955, the rotor for the smaller of the two compressors was the single largest piece of cargo ever received at the Port of Oakland. Southern Pacific Railroad had to take down signal towers and poles from Oakland to Sunnyvale to deliver it to Ames.

Begun in 1951, the UPWT was constructed on an 11-acre site and cost an estimated $32,000,000, including utilities. Construction was completed in 1955 and the tunnel was operational in 1956.



Installation of the 3-stage compressor for the 11-foot Transonic Test Section

Mechanical Features

The Unitary Plan Wind Tunnel consists of an arrangement of three test sections, covering a Mach number range of 0.3 to 3.5, powered by a single system of four tandemly coupled motors driving one of two axial flow compressors. This setup allows the operation of one test section with model installation and preparation in the other test sections occurring simultaneously.

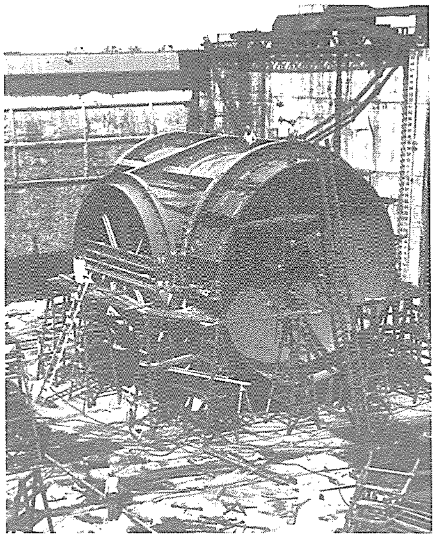
The three test sections are the 11- By 11-Foot Transonic Test Section and the 9- By 7-Foot and the 8- By 7-Foot Supersonic Test Sections. The two supersonic test sections share a common leg and in order to direct the flow to either of the test sections, two large rotating flow diversion valves, one next to the 11-stage compressor and the other at the opposite end of the shared leg were designed. These valves, the largest of their type, are 20 and 24 feet in diameter respectively. Designed to be airtight, the valves weigh over 250 tons each and can be rotated in 25 minutes.

The tunnel shell, a pressure vessel, is constructed of A235 steel in thicknesses varying from 0.5 inches to 2.5 inches and section diameters of 20 feet to 70 feet. Slip type expansion joints using rubber seals provide the ability to anchor the compressors and test sections to maintain the critical alignment of these tunnel portions.

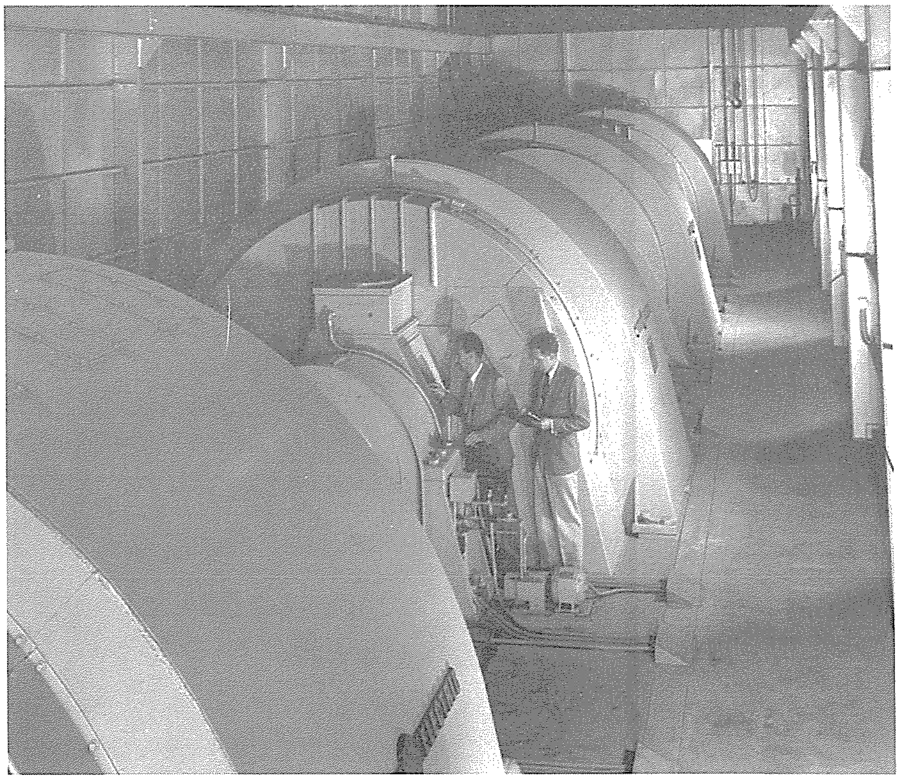
The drive system arrangement has one 3-stage, axial-flow compressor driving the 11-Foot Transonic Test Section and an 11-stage, axial-flow compressor driving either the 9- By 7-Foot or the 8- By 7-Foot Supersonic Test Sections. Either compressor can be disconnected or connected to the drive motors by a set of splined, sliding couplings. The motors can be disconnected from one compressor and connected to the other within 30 minutes. Both couplings are identical and capable of transmitting the full 216,000 peak horsepower from the motors.

The drive motors are rated at 45,000 horsepower each with a 54,000 horsepower one hour overload rating. They are wound rotor induction motors with a slip-regulator speed control system. The drive system employs a electrodynamic braking system on two of the motors to slow the inertia of the attached compressors (the 11-stage compressor rotor weighs 445 tons and the motor rotors weigh 69 tons each) of the drive quickly. This rapid deceleration (about 5 minutes from 700 RPM to 0 RPM) protects the facility from damage should a wind tunnel model start to disintegrate.

Each test section has a separate nozzle configuration to define the optimum for achieving the range of Mach numbers required. Used in the 11-foot Transonic Test Section is a single-jack, flexible-plate nozzle for the Mach range of 1.0 to 1.5. In the 9- By 7-Foot Supersonic Test Section, an asymmetrical, sliding-block nozzle provides a Mach range from 1.5 to 2.5, and in the 8- By 7-Foot, a multijack, symmetrical nozzle provides the Mach number range from 2.5 to



Flow diversion valve for the 9- By 7-Foot and 8- By 7-Foot test sections.



45,000 horsepower main drive motors for the Unitary Plan Wind Tunnel.

TUNNEL SPECIFICS

11-Foot Transonic Test Section:

Mach number: 0.3-1.5

Pressure: 0.3-2.0 Atm. abs.

Reynolds number: 0.3-9.0 million/foot

Test section size: 11 feet high x 11 feet wide x 22 feet long

Nozzle type: Convergent-Divergent single jack point variable moment-of-inertia flexible plate

Angle-of-attack range: ±15°

Angle-of-sideslip range: ±15°

9x7-Foot Supersonic Test Section:

Mach number: 1.5-2.5

Pressure: 0.1-2.0 Atm. abs.

Reynolds number: 0.9-6.5 million/foot

Test section size: 7 feet high x 9 feet wide x 18 feet long

Nozzle type: Convergent-Divergent asymmetric sliding block

Angle-of-attack range: ±15°

Angle-of-sideslip range: ±15°

8x7-Foot Supersonic Test Section:

Mach number: 2.5-3.5

Pressure: 0.1-2.0 Atm. abs.

Reynolds number: 0.7-5.2 million/foot

Test section size: 8 feet high x 7 feet wide x 16 feet long

Nozzle type: Convergent-Divergent multijack (10/side) flexible plate

Angle-of-attack range: ±15°

Angle-of-sideslip range: ±15°

3-Stage Compressor

Rotor weight: 150 tons

Hub diameter: 17 feet

Case diameter: 24 feet

Shaft diameter: 30 inches

Bearings: 2- 30 x 30 inch journals

Blades: 52/stage, 2014T6 aluminum, modified 65 series blower airfoil section, 16 inch root chord, 6 inch tip chord

Stationary stages: 1 variable camber (50% chord hingeline) inlet guide, 3 stator, and 1 exit

Speed: 350-685 RPM

Pumping capacity: 6,250,000 cfm at a pressure ratio of 1.4

Air discharge temperature: 210°F maximum

11-Stage Compressor

Rotor weight: 445 tons

Hub diameter: 18 feet

Case diameter: 24 feet tapering to 20 feet

Shaft diameter: 36 inches

Bearings: 2- 36x54 inch journals

Blades: 1122 solid type 403 steel, modified 65 series blower airfoil section

Stationary stages: 1 inlet guide, 11 stator, and 1 exit

Speed: 700 RPM

Pumping capacity: 3,200,000 cfm at a pressure ratio of 3.5

Air discharge temperature: 450°F maximum

Drive Motors

4 - General Electric wound rotor rated at 45,000 horsepower each (54,000 horsepower one hour overload) tamdemly coupled.

Can be powered singly or up to a maximum of 4 to achieve test conditions.

Speed continuously variable from 350 RPM - 700 RPM using liquid rheostats to vary the secondary resistance.

Electrodynamic braking available by applying D.C. current to the stators and dissipating the energy through the liquid rheostats.

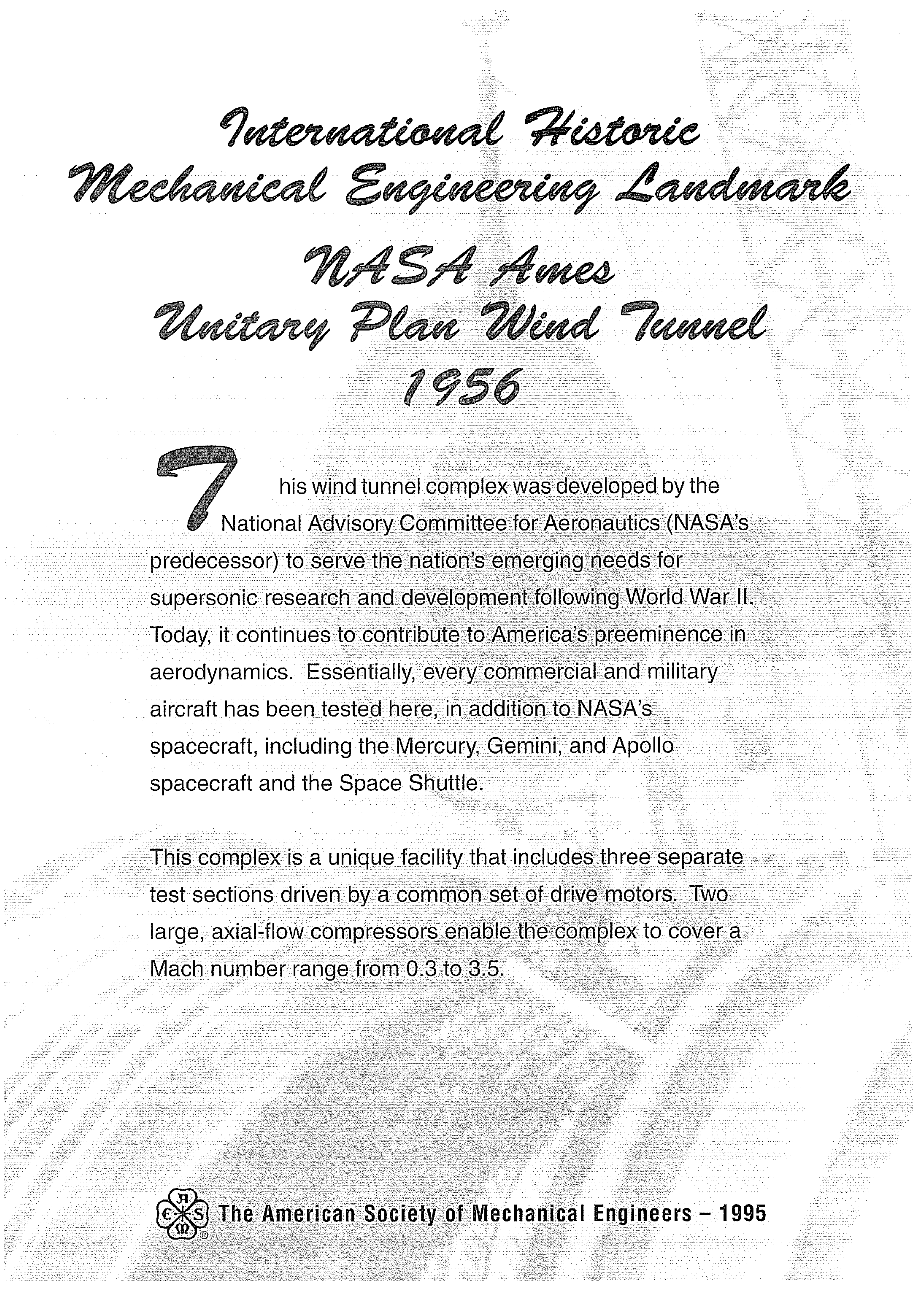
Pressurization Air

Make-Up-Air Compressor:

Pressurization: 50,000 cfm at 140 psig

Evacuation: 5 inches Hg. absolute

Air Dryers: dried to 100 ppm of water by a combination of water and freon direct expansion coils which cool the air to 45°F before it is passed over a desiccant bed of activated alumna.



International Historic Mechanical Engineering Landmark

NASA Ames Unitary Plan Wind Tunnel

1956

This wind tunnel complex was developed by the National Advisory Committee for Aeronautics (NASA's predecessor) to serve the nation's emerging needs for supersonic research and development following World War II. Today, it continues to contribute to America's preeminence in aerodynamics. Essentially, every commercial and military aircraft has been tested here, in addition to NASA's spacecraft, including the Mercury, Gemini, and Apollo spacecraft and the Space Shuttle.

This complex is a unique facility that includes three separate test sections driven by a common set of drive motors. Two large, axial-flow compressors enable the complex to cover a Mach number range from 0.3 to 3.5.

The American Society of Mechanical Engineers – 1995

3.5. The choice of these configurations minimized the overall length of the nozzles.

The nozzle for the 11-Foot Transonic Test Section is shaped to attain Mach numbers from 1.0 to 1.5. A single jacking station is used to deflect a variable moment-of-inertia plate to obtain the desired contour for supersonic flow. A porous test section cancels residual wave reflections. This approach gives better flow characteristics in the test section than the method of expanding the flow from a sonic nozzle into a porous test section. The use of the single jacking station greatly simplified the operating mechanism and reduced cost.

To match the volume flow of the 11-stage compressor with the differing flow requirements of the 8- By 7-Foot Mach 2.5 to 3.5 nozzle, and the 9- By 7-Foot Mach 1.5 to 2.5 nozzle, a bypass is constructed around the 8- By 7-Foot nozzle and reinjected the flow just downstream of the test section. This results in the added benefit of reducing the pressure ratio required to drive the test section.

A make-up-air (MUA) system provides dry air and vacuum to the tunnel. An automatic pressure control system maintains the stagnation total pressure to control the Reynolds number.

The MUA system includes an air compressor with intercoolers and an aftercooler, a dryer, dry air storage tanks and an evacuator. Stagnation pressure is controlled from 0.1 to 2.0 atmospheres. Humidity is controlled to 100 parts-per-million of water. The make-up-air compressor has a pressure ratio of 10. Dry air is pumped into storage tanks, equal in volume to the wind tunnel, via the compressor through a dryer, to 150 psia. Once the tanks are full, the more humid air is evacuated from the tunnel using the same compressor. The storage tanks are then opened, filling the tunnel with dry air.

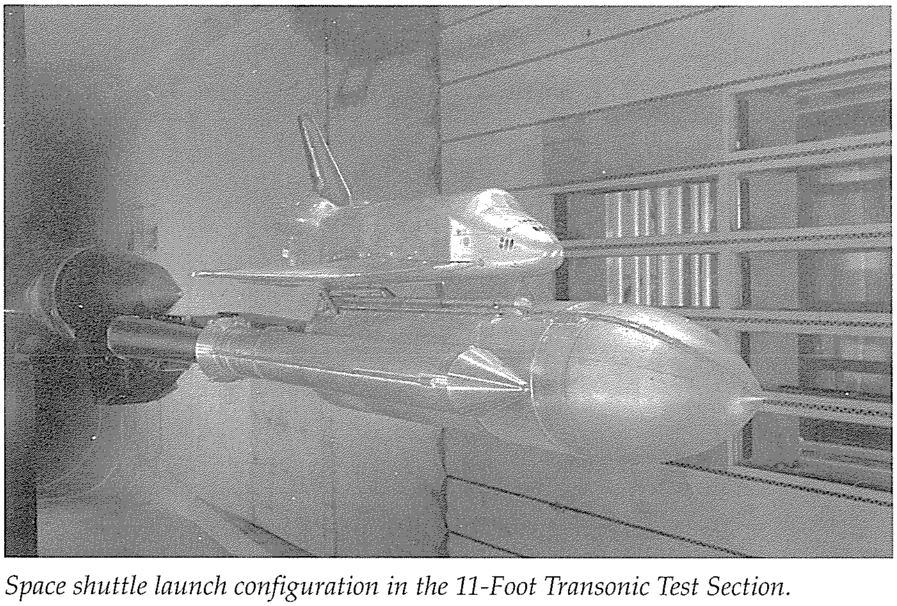
Stagnation temperature is controlled. The cooling system consists of an aftercooler downstream of each compressor fed by water from an evaporative-type cooling tower. The aftercoolers, 45 feet in diameter for the Supersonic Test Section and 70 feet in diameter for the Transonic Test Section, are assembled from commercial, rectangular heat exchanger units, one unit thick, stacked to cover as much as possible of the circular cross section of the cooler shell. The portion of the cross section not covered by the units is baffled to prevent flow from bypassing the exchanger units.

Historical Significance

Since beginning operation in 1956, the Ames Unitary Plan Wind Tunnel has played a major role in the development of civilian and military jet aviation. It is one of the most heavily used wind tunnel facilities in the United States. The Ames UPWT has operated 24 hours per day for 5 to 7 days per week since it was placed into service. The drive system has accumulated over 70,000 hours of operation which is the equivalent of a continuous 24 hours per day, 7 days per week operation for over 8 years.

The facility has tested commercial jet transports from the Douglas DC-8 to the McDonnell-Douglas MD-12 and the Boeing 777. The impact that U.S.

V/STOL configuration in the 11-Foot Transonic Test Section.



Space shuttle launch configuration in the 11-Foot Transonic Test Section.

commercial aviation has had on the world is well known and the Ames facility has played a major role in that development.

The contribution of the UPWT to supersonic flight has been enormous with the testing of every military aircraft designed since beginning its operation, including the YF-12, SR-71, lifting bodies like the M2, and configurations representing America's initial and current involvement in supersonic transports. These tests include cruise performance, lateral and longitudinal stability, structural loads, and aeroelastic and dynamic loads measurements.

The Ames facility has also played a heavy role in the nation's space program. Aerodynamic testing has been performed on the Mercury, Gemini, and Apollo spacecraft and the Space Shuttle. Over 20,000 hours of testing was conducted on the Shuttle, including the cold-jet simulation of the rocket plumes to study the effect of the plumes on the orbiter and launch configuration, the study of the complex flow field between the orbiter, tank, and solid rocket boosters, the shock wave impingement on the heat protection system, and other phenomena that were difficult or impossible to analyze by any other means.

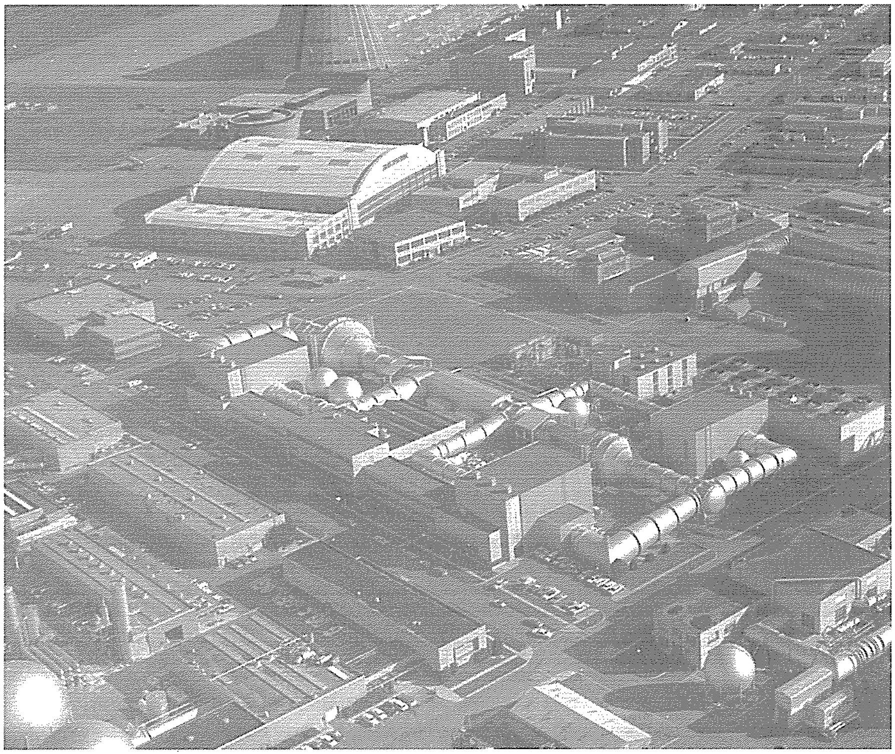
Currently, the Ames Unitary Plan Wind Tunnel is contributing to maintaining U.S. preeminence in aeronautics by testing configurations of the High Speed Civil Transport and the Advanced Subsonic Transport, as well as future military configurations.

Present Day

The facility normally operates 24 hours per day, 5 to 7 days per week. However, the facility is currently not operating while it is undergoing a $85 million modernization project. This modernization is being done in response to industry calls to reduce the cost of conducting wind tunnel tests, which can cost up to $300K for a one week test, and to allow more access to the wind tunnels. Prior to shutdown for the modernization, the 11-Foot Transonic Test Section had a 2.5-year backlog of tests.

The modernization will increase test productivity by automating the control system; improve the flow quality of the Transonic Test Section by installing honeycomb flow straighteners, turbulence reduction screens, and segmented flaps in the wide angle diffuser (to eliminate separation of the flow); and improve the safety of operation and efficiency of the compressor for the Transonic Test Section by installing composite rotor blades. The facility is scheduled to resume operation in late 1997.

The Ames Unitary Plan Wind Tunnel is an operating facility that is, at times, closed to non-test personnel when restricted access testing is occurring. However, tours of Ames Research Center, available through the public affairs office, often include the UPWT. Organizations may request a specific tour of this facility through the public affairs office.



Aerial view of the Unitary Plan Wind Tunnel.

The History and Heritage Program of ASME

The ASME History and Heritage Recognition Program began in September 1971. To implement and achieve its goals, ASME formed a History and Heritage Committee, initially composed of mechanical engineers, historians of technology, and the curator emeritus of Mechanical and Civil Engineering at the Smithsonian Institution. The Committee provides a public service by examining, noting, recording, and acknowledging mechanical engineering achievements of particular significance. The History and Heritage Committee is part of the ASME Council on Public Affairs and Board on Public Information.

The Unitary Plan Wind Tunnel is the 45th International Historic Mechanical Engineering Landmark to be designated. Since the ASME History and Heritage Program began, 173 Historic Mechanical Engineering Landmarks, 6 Mechanical Engineering Heritage Sites, and 6 Mechanical Engineering Heritage Collections have been recognized. Each reflects its influence on society, either in its immediate locale, nationwide, or throughout the world.

An ASME landmark represents a progressive step in the evolution of mechanical engineering. Site designations note an event or development of clear historical importance to mechanical engineers. Collections mark the contributions of several objects with special significance to the historical development of mechanical engineering.

The ASME Historical Mechanical Engineering Recognition Program illuminates our technological heritage and service to encourage the preservation of the physical remains of historically important works. It provides an annotated roster for engineers, students, educators, historians, and travelers, and helps establish persistent reminders of where we have been and where we are going along the divergent paths of discovery.

For further information, please contact Public Information, the American Society of Mechanical Engineers, 345 East 47 Street, New York, NY 10017-2392, (212) 705-7740; fax (212) 705-7143.

The American Society of Mechanical Engineers

Daniel T. Koenig, President
Sundaram Krishnamurthy, P.E., Vice President, Region IX
Louis A. Povinelli, Vice Chair, Aerospace Division
George I. Skoda, P.E., History & Heritage Chair, Region IX
John R. Parker, Senior Vice President, Public Affairs
Erwin Fried, P.E., Vice President, Public Information
David L. Belden, P.E., Executive Director
Lynden Davis, Director, Western Regional Office

The ASME History & Heritage Committee

J. Lawrence Lee, P.E., Chair
Robert M. Vogel, Secretary
William DeFotis
Burton Dicht
Robert B. Gaither
R. Michael Hunt, P.E.
William J. Warren, P.E.
Richard S. Hartenberg, P.E., Emeritus
Euan F.C. Somerscales, Emeritus
Joseph Van Overveen, P.E., Emeritus
Diane Kaylor, Staff Liaison

The ASME Aerospace Division

Dennis M. Achgill, Chair
Louis A. Povinelli, Vice Chair
Barney F. Gorin, Secretary
Terrence A. Weissharr, Treasurer

The ASME Santa Clara Valley Section, Landmark Committee

Daniel Petroff, P.E., History & Heritage Chair
Julie A. Pollitt, Tom Roberts, Lilia Sanchez

National Aeronautics and Space Administration

Daniel S. Goldin, Administrator

National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, CA 94035-1000