

# Facility Description *skip 0.2 in* 8-Foot Transonic Pressure Tunnel

Langley Research Center *skip 0.2 in*  
National Aeronautics and Space Administration

• does not include:

- sting, hardware sketches
- balance information

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# Facility Description

## 8-Foot Transonic Pressure Tunnel

### Summary

This report presents a description of the National Aeronautics and Space Administration 8-ft Transonic Pressure Tunnel (8-ft TPT) complex. It also provides an historical perspective of the tunnel, limited reference information, and general information to be used as a guide during test preparation. It is not intended as a users guide for test operations but some information related to test equipment and procedures are included.

### Introduction

This report presents a description of the National Aeronautics and Space Administration 8-ft Transonic Pressure Tunnel (8-ft TPT) complex. It has a fourfold purpose: first, to provide an historical perspective of the tunnel and its auxiliary equipment; second, to provide reference information for current facility staff; third, to provide a fairly comprehensive facility description for new staff members; and fourth, to provide potential facility users with general information to be used as a guide during test preparations. Although it is not intended as a users guide for test operations, some information related to test equipment and procedures is included.

This report should not be regarded as the only source of information regarding the facility. As with any wind tunnel, modifications to the tunnel itself, its auxiliary equipment, test hardware, and data acquisition and reduction systems take place on a continuing basis. Direct contact should, therefore, be established with facility personnel whenever a question arises.

## Symbols

|          |                                      |
|----------|--------------------------------------|
| $b$      | model span                           |
| $l$      | model length                         |
| $M$      | Mach number                          |
| $P$      | applied static load                  |
| $R$      | Reynolds number based on unit length |
| $S$      | model planform reference area        |
| $\alpha$ | model angle of attack                |
| $\Delta$ | incremental amount                   |
| $\delta$ | sting deflection angle under load    |

### Abbreviations:

|            |   |
|------------|---|
| <i>cfm</i> | cubic feet per minute                         |
| ESP        | electroscanning pressure                      |
| <i>gpm</i> | gallons per minute                            |
| <i>hp</i>  | horsepower                                    |
| LaRC       | Langley Research Center                       |
| NACA       | National Advisory Committee for Aeronautics   |
| NASA       | National Aeronautics and Space Administration |
| NF         | Normal force                                  |
| <i>psf</i> | pounds per square foot                        |
| <i>psi</i> | pounds per square inch                        |

### Subscripts:

|          |                              |
|----------|------------------------------|
| $\infty$ | conditions in the freestream |
|----------|------------------------------|

### Tunnel designations:

|           |  |
|-----------|--|
| BARF      | Basic Aerodynamic Research Facility      |
| DFA       | Diffuser Flow Apparatus                  |
| 8-ft. HST | Langley 8-Foot High Speed Tunnel         |
| 8-ft. TT  | Langley 8-Foot Transonic Tunnel          |
| 8-ft. TPT | Langley 8-Foot Transonic Pressure Tunnel |
| 2-ft. HF  | Langley 2-Foot Hypersonic Facility       |

## Location and Organization

The 8-ft Transonic Pressure Tunnel (8-ft TPT) is located in Building 640 (640 Thornell Ave.) on the southwest branch of the Back River in the East Area of Langley Air Force Base, Hampton, Virginia. Offices for the engineering staff associated with the facility are located in Building 641 (641 Back River Road) which is contiguous to Building 640.

Most Langley Research Center offices and facilities are located in the West Area of Langley Air Force Base—only a few of the older major wind tunnel facilities remain in the East Area.

The facility is managed by the Transonic Aerodynamics Branch, an organizational unit within the Applied Aerodynamics Division of the Aeronautics Directorate. Since the 8-ft TPT became operational in 1952 the managing branch has been identified as the 8-Foot Transonic Tunnels Branch, the 8-Foot Tunnel Branch, the Transonic Aerodynamics Branch, the Airfoil Aerodynamics Branch, the Fluid Dynamics Branch, the Advanced Configurations Branch and currently, again, as the Transonic Aerodynamics Branch. Technician support for the facility is provided by the Tunnels Operations Branch and electrician support is provided by the Electrical Support Branch. Both branches are in the Operations Support Division of the Systems Engineering and Operations Directorate.

## Facility Background

The 8-ft TPT was constructed on the same site and used much of the same main drive electrical control equipment as its predecessor, the National Advisory Committee for Aeronautics (NACA) 8-Foot High-Speed Tunnel (8-ft HST) which became operational in 1936. As discussed later, the 8-ft HST was modified in 1950 and designated as the 8-Foot Transonic Tunnel (8-ft TT).

The 8-ft HST was NACA's first high speed tunnel large enough to test sizeable models of complete aircraft on a continuous basis (ref. 1). Figure 1 shows photographs of the early 8-ft HST and figure 2 shows a planform sketch of the tunnel. As shown in figure 1 the tunnel was built next to the Full Scale Tunnel, between the Propeller Research Tunnel and the river. <sup>1930's</sup> The complex included a one and two story combination office-shop building facing the river. The one story wing at the southern end of the building housed the entrance to the test section plenum. The one and one-half story wing at the northern end of the building was set back from the central two story portion of the building and housed the main drive motor.

The 8-ft HST was built using Depression-era labor forces and was constructed of reinforced concrete. It had an igloo-shaped plenum structure around the circular test section with walls 1 ft

thick. This igloo was essentially a low-pressure chamber. Operating personnel located inside the igloo were subjected to low pressures and had to wear oxygen masks and enter through airlocks. The heat exchanger shown above the tunnel in figure 1 was required to remove the mechanical energy of the fan added to the airstream as heat. A small amount of heated air was bled off the tunnel walls and released outside, removing its contained heat in the process. The discharged hot air was replaced by cool air pulled in from the outside. The heat bled off in this manner equaled the heat added by the fan—in this case the removal of only about 1 percent of the mainstream airflow was required.

include photo of "blast room" beneath test section

The closed, circular test section was 8 ft in diameter and, with a large two-stage fan driven by an 8 000 hp motor, attained airspeeds of 575 mph ( $M_\infty = 0.75$ ). Each stage was 16-ft diameter with 18 blades. Synchronous speed of the 8 000 hp motor was 900 RPM and speed control was provided by a liquid-rheostat system.

In the early 1940's, a two story frame shop-office addition was built on the southern end of the original office building as shown in figure 3.

In December, 1943, the 8 000 hp motor failed and was replaced with a larger 16 000 hp motor. The first run with the new motor was made in February of 1945 and subsonic Mach numbers up to 0.99 were achieved before choking occurred at or near the model in the test section. The motor produced 16 000 hp at 820 RPM and had a synchronous speed of 880 RPM. In order to run higher RPM and generate more horsepower, a Kraemer speed control system was included which allowed the motor to go through synchronous speed to 990 RPM where 22 000 hp could be drawn for short periods of time (generally about 1/2 hour). A two story Electrical Equipment Building was added behind the main drive motor house to contain the Kraemer system equipment and is shown in the 1946 photographs of figure 4. The electrical controls for the Kraemer system were located on the second story (fig.4(j)). Figure 4(k) is a photograph of the Propeller Research Tunnel immediately behind the 8-ft HST that was later torn down to make room for the 8-ft TPT.

In the mid 1940's investigations showed that interference due to solid blockage in wind tunnels operating at subsonic speeds could be minimized with slotted test sections. These investigations also showed that slotted test sections eliminated closed tunnel choking limitations and permitted operation at low supersonic speeds (ref.2). The quickest way to apply this new concept was to modify the operational 8-ft HST to a slotted test section configuration and, in 1950, the tunnel was reconfigured with a slotted test section (fig. 5) and designated as the 8-Foot Transonic Tunnel (8-ft

TT). Along with the modification of the test section, the fan blades were replaced and a new drive train installed. Reference 3 describes some of the slotted wall development work in this tunnel.

At about the same time, a new facility, designed from its inception around the new slotted wall concept and which included the capability to vary stagnation pressure, was constructed on the site of the Propeller Research Tunnel, behind the 8-ft TT, and became operational in 1952. This new tunnel was designated as the 8-Foot Transonic Pressure Tunnel (8-ft TPT). The building associated with the facility was identified as Building 640. The first floor of Building 640 was used to house auxiliary equipment associated with the facility, the second floor housed the control room and airlock entrance to the tunnel plenum, and the third floor was used as a model-preparation and shop area.

Figure 6 shows photographs of the 8-ft TPT taken in the fall of 1952 as construction was nearly complete. The river bank in front of the office building was filled in for construction of a three-cell cooling tower and for parking. The frame addition to the original office building was torn down and two new wings were added—one at either end of the original office building. These new wings were perpendicular to the original office building and extended beyond the old sea wall onto the newly filled river bank. The modified office building was identified as Building 641. The 8-ft Transonic Tunnel remained in place and the entrance to the concrete igloo was incorporated into the new office building. At present, the interior of the igloo is used as an office/storage area and usually referred to as the "dome". The motor house for the 8-ft TT and the building (Electrical Equipment Building) behind it which contained the Kraemer speed control system was incorporated as part of Building 641 and used to house the air conditioning equipment for Building 641.

When Building 640 was constructed in the early 1950's, operating controls for the 8-ft TPT were grouped in front of a four-panel observation window in the plenum wall surrounding the test section that permitted operators to view models during testing. Figure 6(d) is a photograph showing the observation window and control panel and figure 6(e) shows the free standing graphics control board. Figure 6(f) shows the control panel for the 10,000 cfm compressor located on the first floor. The present-day, enclosed control room on the second floor of Building 640 was not constructed until the mid-1960's. ✓

Note in the photograph of figure 6(b) the three-cell cooling tower on the river bank northeast of the facility. Each cell included a flat three-bladed fan with a wooden shroud on the top. In 1956, a fourth cell with a four-bladed fan was added on the northern end of the cooling tower as shown in the 1967 photograph of figure 7. This fourth cell was included as part of the cooling apparatus associated

with the addition of two 100 000 cfm compressors discussed in following paragraphs. In 1972, a fire damaged the cooling tower and repairs included the replacement of the original three-bladed fans with new eight-bladed cambered fans and fiberglass shrouds.

*In 1991, the  
two cell tower  
was demolished  
and replaced  
with a new  
tower with  
two fans.*

The drive motor for the new 8-ft TPT had a synchronous speed of 720 RPM and the Kraemer system used with the 8-ft HST and 8-ft TT was modified with the addition of a Scherbius system to permit overspeed to 840 RPM. The Scherbius equipment was located in the northeast corner of Building 640 immediately adjacent to the Kraemer system which, as noted above, was located in the northwest corner of Building 641. Controls for the Scherbius modified Kraemer system were incorporated into the electrical controls on the second floor of the room housing the Kraemer system. This area became to be known as the "mezzanine" since it overhangs the high bay area in the northwest corner of Building 640 in the form of a balcony.

The wooden fan blades in the 8-ft TT were replaced with epoxy plastic blades in 1957 and operation of the two 8-ft transonic facilities overlapped for several years before the 8-ft TT was deactivated in 1961. In 1985 the 8-ft TT was designated as a National Historic Landmark.

Even though the tunnel was deactivated in 1961, the 16 000 hp motor, the drive shaft, and the fans were kept in operational condition. The drive shaft and fans were rotated as a scheduled maintenance procedure until 1976 when it was decided that scheduled rotation was not necessary. In the early 1980's the fan blades, hub, nacelle, and shaft, and the turning vanes immediately upstream of the fan were removed and sent to Wright Patterson AFB for use in the construction of a new facility, the Subsonic Aerodynamic Research Laboratory (SARL). The 16 000 hp motor (fig. 4(b)), however, is still in place (Rm. 115, Building 641).

In the mid 1950's an air removal system with two 96 000 cfm compressors manufactured by the Elliott Corporation was installed on the first floor of Building 640 to provide plenum suction for test section wall boundary layer control. Although these compressors have a rated capacity of 96 000 cfm, they are referred to as the 100 000 cfm compressors, or as the "Elliotts". Installation was completed in 1956 and, after some operational difficulties, the compressors became fully operational in 1958. These two large compressors were also used for plenum suction in the 8-ft TT while it was still in operation and for powering an injector-driven, continuous flow hypersonic research facility (2-Foot Hypersonic Facility) located on the third floor of Building 640 at Mach numbers from 3 to 7 (ref. 4). This hypersonic facility was operational from 1958 to 1970. It was then idle until the mid 1970's when it was modified to simulate and evaluate critical components of the National Transonic

Facility (NTF) and referred to as the Diffuser Flow Apparatus (DFA). Reference 5 describes this apparatus. Following the diffuser flow research, the facility on the third floor was used for various research projects until the mid 1980's when it began to be used for basic research using advanced flow diagnostic techniques and was identified as the Basic Aerodynamic Research Facility (BARF) in 1986. In early 1990, the BARF was removed to make room for a model preparation area. All exterior piping associated with the facility was retained, however.

In 1965, the 8-ft TPT was involved in the evaluation of three company versions of the C-5A and three temporary rooms were built in the high bay northwest corner of Building 640 next to the Scherbius equipment. These rooms, used for model work and data storage and approximately 10 by 12 ft each, were wrapped in a heavy metal mesh, approved for storage of classified material, and referred to as the "secret rooms". Following the C-5A evaluation, these rooms were used for storage until 1990 when one of the rooms was removed to allow replacement of a transformer. In 1991, the remaining two rooms were demolished.

In 1981, a honeycomb and five screens were permanently installed in the settling chamber upstream of the test section to improve the flow quality of the facility in support of the laminar-flow-control experiment (ref. 6). General characteristics of the honeycomb and screens are presented in a following section of this report and detailed design features and installation procedures are presented in reference 7. In conjunction with the laminar-flow-control experiment, a temporary 54-ft contoured test section liner was installed in the tunnel in 1981 to simulate unbounded flow about a swept airfoil model with infinite span. This liner, also described in references 6 and 7, was removed at the conclusion of the experiment in 1988. Taking into account the time required for installation and removal of the liner and the fact that the liner was designed for a freestream Mach number of 0.82 the tunnel was not run at speeds above about 0.82 between 1980 and 1989.

Figure 8 shows a photograph of the facility taken in 1971. In 1984, Building 641 underwent an extensive rehabilitation and two outside, enclosed stairways (one on each wing) were constructed. More recent photographs of the facility, taken in 1988, are shown in figure 9.

## Research Highlights

Over the years the 8-ft Transonic Pressure Tunnel has been considered more of a research orientated facility than a production facility. In addition to a wide range of more or less routine testing; including performance and stability measurements, configuration development, propulsion integration, semispan models, flow diagnostic measurements, and drag reduction, a number of new,

innovative aerodynamic concepts have been tested. For example, the concept of area ruling to permit flight through sonic velocity, as well as winglets, supercritical airfoils, laminar flow control, and sonic transports (have been) developed in the 8-ft Transonic Pressure Tunnel. Many novel and unique experiments have been conducted in the facility. One such novel experiment, conducted in the mid-1960's, involved attaching variable position flaps to the turning vane support structure in the settling chamber upstream of the test section (see fig. 10) in an attempt to twist the flow over a model in the test section to simulate variable wing twist.

Although not designed as a two-dimensional tunnel, the geometry of the test section (discussed in following sections) permits testing of an airfoil model with a large chord and large span-to-chord ratio, both of which are desirable for two-dimensional tests. In addition, the ratio of sidewall-displacement-thickness to tunnel width is small, which tends to minimize sidewall-boundary-layer effects. For example, tests have been conducted (ref. 8) on the classical NACA 0012 airfoil which has long been a standard two-dimensional model for evaluating wind-tunnel test techniques and computational methods and for making comparisons between data obtained in different wind tunnels. Because of its suitability for two dimensional testing the tunnel was also used in the development of the supercritical airfoil concept (ref. 9) in the 1960's and 1970's.

## General Description of Facility

The Langley 8-Foot Transonic Pressure Tunnel is a closed-circuit, single-return, variable-density, continuous-flow, slotted-throat tunnel capable of operating at stagnation pressures from about 0.25 atm. to 2.0 atm. and over a Mach number range from 0.2 to 1.3. Air is circulated through the circuit by an axial compressor located downstream of the test section diffuser and driven by an electrical drive system. The rate of mass flow of air through the tunnel with the flow choked at  $M_\infty = 1.0$  with one atm stagnation pressure and 120 ° F is approximately 2 360 lbs/sec. The approximate volume of the tunnel circuit, including the plenum chamber, is 275 000 ft<sup>3</sup>.

## Operating Characteristics

The tunnel-empty operating envelopes for the facility in terms of stagnation pressure plotted as a function of Mach number are shown in figure 11. The maximum continuous freestream stagnation pressure operating envelope for the tunnel is about 2 atm at  $M_\infty = 0$ , falls off to about 1.4 atm at  $M_\infty = 0.8$ , and falls off further to about 1 atm at  $M_\infty = 1.2$ . This continuous operating limit line represents the generally maximum tunnel conditions that may be run on a continuous basis

without overheating the electrical equipment. Stagnation pressure is maintained by means of semi-automatic controls in conjunction with compressors which will be described later. Corresponding dynamic pressure and Reynolds number envelopes are also shown in figure 11. The continuous operating limits may be exceeded for increasingly shorter periods of time up to the dashed limit line. This line represents the maximum stagnation pressure which may be run without exceeding the power limits of the electrical system or the aerodynamic loads across the screens. As these higher stagnation pressures are approached, the electrical equipment begins to absorb more and more heat, thus limiting the time which may be spent at these conditions before overheating occurs.

During calibration of the empty test section using a centerline probe, it has been observed that a Mach number of exactly 1.10 can not be run because it falls in a RPM dead region associated with the synchronous speed of the main drive. Thus, there is a narrow band of Mach numbers around 1.10 which can not be run. The center of this band depends on the size model and the amount of blockage in the test section which influences the RPM required to achieve a given Mach number. The setting of the diffuser spoilers, discussed in following sections, also influences where this dead band occurs.

Based upon both centerline probe and wall pressure measurements, generally uniform flow is achieved over a test section length of at least 50 in. at Mach numbers from 0.20 to 1.20. The higher the Mach number, the shorter the region of uniform flow becomes. Local deviations from the nominal free-stream Mach number increases with increasing Mach number and range from about  $\pm 0.002$  at subsonic speeds to  $\pm 0.005$  at a Mach number of 1.20. Early calibrations considered the calibrated region of the test section to extend from the 78-in. station to the 118-in. station. A calibration performed in 1972 used an average between the 70-in. station and the 120-in. station. Neither stagnation pressure nor temperature appear to have any significant effect on the calibration of the tunnel.

The centerline Mach number distributions shown in figure 12 are from the most recent calibration performed in 1989.

The tunnel is capable of achieving Mach numbers to about 1.3 if the Elliott compressors are used but most testing is limited to a maximum Mach number of 1.2 since the calibrated region of the test section for  $M_\infty = 1.3$  is much shorter and further downstream than for lower Mach numbers and requires that a model be located further aft in the test section.

When the tunnel is run using both Elliotts for test section boundary layer suction, a lower fan

RPM is required for a given Mach number and the tunnel can run up to a Mach number of nearly 1.33 at 1 atmosphere (see the limit line with Elliotts, fig. 11). but the calibrated region of the test section moves downstream to between approximately the 140-in. and 165-in. stations. At  $M_\infty = 1.30$ , operation of the Elliotts have to be backed off to just below "full operation" to avoid a rough region in the main drive speed control around 820 RPM and the calibrated region of the test section is downstream of approximately the 135-in. station. In order to run  $M_\infty = 1.25$  it is necessary to run above synchronous RPM and operate the Elliotts a little below "full operation". At  $M_\infty = 1.25$ , however, the only flat local Mach number distribution occurs between approximately the 120-in. and 140-in. stations. At  $M_\infty = 1.20$  with full Elliott operation, there is a sharp drop in the local Mach number distribution at approximately the 130-in. station. At  $M_\infty = 1.15$ , this sharp drop moves forward to approximately the 120-in. station, at  $M_\infty = 1.10$ , to the 110-in. station, and at  $M_\infty = 1.05$ , to the 100-in. station. With less than "full operation" of the Elliotts, the drop off in local Mach number occurs at a more rearward location but there is still a gradient in the Mach number distribution. The 100 000 cfm compressors are not normally used below a Mach number of 1.0 since they tend to skew the test section Mach number distribution. Generally, when using the Elliotts, they are operated at the minimum suction required to compensate for model blockage to avoid adverse effects on the Mach number distribution in the test section. They would be used at full suction only if a Mach number above 1.20 was desired. If full Elliotts were used at the higher Mach numbers, careful attention would have to be paid to where the model was located.

always  
use  
"full"  
suction!

### General Configuration

Figure 13 shows an artist conception of the tunnel with cutaway views of various components, figure 14 shows a planview of the tunnel, figure 15 shows schematics of the various auxiliary pumping circuits, and figure 16 shows a drawing of the slotted-throat and diffuser-entrance regions of the tunnel. Figure 17 shows schematic layouts of the 8-ft TPT and auxiliary equipment on the three floors of Building 640. Figure 18 shows photographs at various stations around the interior of the tunnel beginning at the turning vanes immediately downstream of the test section and proceeding clockwise around the circuit. Figure 19 shows photographs around the exterior of the tunnel complex beginning with the northeast corner and proceeding clockwise around the perimeter of the tunnel.

The tunnel is primarily circular in cross section except for the test section, which is 85.51 in. square at the slot origin, heavily filleted, and connected to the circular entrance contraction and to the circular part of the diffuser by means of transition sections (fig. 14). An interior air lock on

the second floor of Building 640, equipped with two air-tight doors and relief valves, is provided to permit access to the plenum around the test section. Access to areas of the tunnel other than the plenum is provided by means of exterior hatches which are sealed when closed. The largest diameter of the tunnel is 36 ft in the settling chamber upstream of the test section and the cross-sectional area of the throat (see following section on Test Section) is approximately the same as that of an 8-ft-diameter circle, so that the contraction ratio is 20.24:1. When account is taken of the fairing around the circumference of the screens and honeycomb (see following section on Screens and Honeycomb) the contraction ratio drops to 18.41:1.

The flow is turned at the corners by means of turning vanes (figs. 13 and 14) which, except for those at Ring A immediately upstream of the main drive fan blades, are made of curved steel plates. The vanes at Ring A are hollow and have open trailing edges to permit introduction of dry air into the tunnel and return of suction exhaust to the circuit.

Catch screens are attached to the bottom of the downstream face of the turning vanes at Ring A (fig. 18(b)) and at the bottom of the upstream face of Ring D (fig. 18(j)) to prevent debris from hitting the fan blades or getting into the cooling coils.

Sometime in the 1950's an attempt was made to install a debris screen at Ring A by installing horizontal bars about an inch apart over the entire downstream face of the hollow turning vanes. The bars were inserted in notches cut into extensions welded on the trailing edges of the vanes. These bars were removed and replaced by the catch screen on the floor when repeated damage to the bars due to acoustic loads occurred. The notched extensions in the hollow trailing edges are still present (fig. 18(c)).

### **Tunnel Shell**

The pressure loads are taken on a steel shell reinforced by steel rings and supported by roller and flexible steel columns. The steel shell is covered with an acoustic and insulation blanket consisting of a blown type concrete material (referred to as shotcrete or gunite) sprayed over a wire mesh.

The tunnel body is suspended on columns with the tunnel horizontal axis 46 ft above the ground level. The supports on the short legs of the tunnel, with the exception of the fixed supports at the main motor bearings, are on rollers for tunnel expansion relief. The columns on the long legs of the tunnel are rigidly fastened to the tunnel body and bend with tunnel expansion. Two flexible, hinged, expansion joints in the short leg of the tunnel ahead of the test section are designed to relieve any unsymmetrical expansion. Tunnel expansion is small, on the order of 0.9 in. in the long leg of the

tunnel.

The roller support columns in the short legs of the tunnel are constructed of reinforced concrete with steel toppings (fig. 19(-)) which contain roller mechanisms welded to the tunnel shell. The flexible columns (fig. 19(-)) are of steel, box beam construction.

The tunnel shell around the 36-ft-diameter settling chamber section extends downstream around the test section to form a surrounding closed plenum or chamber (figs. 13 and 14). Access to this plenum is through a two-way air lock with 4-ft x 8-ft doors. Pieces of equipment too large for the airlock doors may be brought in through a 10-ft by 15-ft door in the lower east quadrant of the plenum although this access door has not been used in recent years. Use of this large hatch is restricted by several air and hydraulic lines which pass through penetration holes in the hatch.

The tunnel is operated from a control room located in front of a large, four-segment, observation window in the west side of the plenum (fig.20). Seventeen additional, smaller ports for observation are provided in the wall of the plenum—nine grouped around the large observation window and eight in the ceiling. The nine observation ports around the large window are distributed with four located in a small upper observation room nestled around the periphery of the plenum above the control room, three located in a small lower observation room nestled around the periphery of the plenum below the control room, and one located on either side of the large window. The eight observation ports in the plenum ceiling are located in the floor of a long, narrow, L-shaped observation room on the third floor. Several of these ports are used as plenum wall penetrations for various electrical and pressure instrumentation and the remainder are taped over to protect the glass and to provide security for classified model testing. Additional manifolds are provided in the wall of the plenum near the control room for pressure and electrical leads.

There are two electrically-operated 15-ton traveling-bridge cranes running on tracks in the plenum above the test section for moving heavy objects. One of these cranes, the downstream one, is used to support and translate the schlieren system along the test section.

### Main Drive

Power for the tunnel fan is supplied by a General Electric wound-rotor induction motor and speed control up to 840 RPM is provided by means of the modified Kraemer system that permits operation above synchronous speed. With this system a desired speed can be maintained constant within 1/4 percent at RPM's greater than 200 and within 1/2 percent at lower RPM's.

The continuous rating of the motor is 22 500 hp with 25 000 hp available for short term operation

*Suby installing launchers*

(usually about one hour). The motor is designed to deliver power proportional to the cube of the rotational speed up to 650 RPM at which point the rated power is 20 000 hp. Above this speed the power output is linear with revolution speed up to 22 500 hp at 800 RPM with 5-percent overspeed capability to 840 RPM in case the motor does not absorb this power at 800 RPM. For speeds less than 800 RPM the designed power absorption of the fan is less than the designed output of the motor, so that some power margin is available in case the fan power absorption exceeds the designed values.

### Motor House

The main drive motor is housed in the motor house at the south east corner of the tunnel (figs. 8 and 13). It is built on three levels with open metal grids between the levels to allow recirculation of cooling air. There is a manually operated hoist of 2-ton capacity and a monorail in the third floor ceiling above the motor.

The first floor is used as a limited storage area and contains a fire protection sprinkler system (fig. 21(a)) and the main motor downdraft air cooler (figs. 21(b)). The piping on the left of the cooler in figure 21(c) is the cooling tower water supply and return piping. The duct over the cooler goes up through the second level (fig. 21(d)) and terminates directly under the shrouded element of the main drive motor (fig. 21(e)). There is an enclosed fan inside the duct which pulls air from the third floor level, through the shroud, across the motor, down through the duct, and through the cooler on the first floor level. From there, the air is recirculated back up through the open grids to the third floor level. Figure 21(f) shows the main drive lubrication system on the second floor level next to the cooling air duct.

As may be seen in the photograph of figure 21(g), provision was made in the motor house for enough extra space on the third floor to house a second drive motor in tandem with the existing motor or to replace the existing motor with a single larger motor if the need ever arose.

Figures 21(h) and (i) are photographs showing the end of the main drive motor where the fan drive shaft passes through the tunnel shell. Prevention of air leakage at the position where the drive shaft penetrates the tunnel wall is accomplished by an oil type seal containing a series of labyrinths.

### Shaft and Nacelle Fairings

*Shaft fairing.* The shaft is shielded from the airstream by a fairing which extends from the inside of the tunnel shell through the turning vanes at Ring A to the nacelle nose fairing (figs. 18(-)

through 18(-)). This fairing is vented at the tunnel shell.

*Nacelle nose fairing.* The nacelle nose fairing is supported by the upstream fan bearing support ring and is joined to the shaft fairing by a slip joint. It contains a baffle fitted close to the shaft to prevent excessive flow of air into the nose fairing from the shaft fairing. The nose fairing contains an inwardly hinged access hatch on its lower upstream surface.

*Nacelle center fairing.* The center region of the nacelle fairing between the fan bearing rings is supported by the bearing support rings. The fairings are designed so that it is possible to remove both the upstream and downstream sections through 3-ft by 4-ft and 4-ft by 4-ft hatches in the tunnel shell with the fully assembled fan in place. The ratio of the nacelle diameter to the tunnel diameter is 0.7

*Nacelle tail fairing.* The upstream end of the nacelle tail fairing contains nine inwardly opening circumferential inspection hatches, is supported on the downstream fan bearing support ring, and is connected to the downstream end of the tail fairing through a slip joint. The remainder of the tail fairing is supported by the downstream straightening vanes, three elliptical struts near its midsection, and a connection to the turning vanes splitter plate at Ring B. It contains two inwardly opening personnel hatches in the bottom.

### Drive Fan

The power is absorbed by means of a compressor located in the short leg at the south end of the tunnel. This compressor is composed of a single stage rotor or fan with 32 fixed pitch blades followed immediately downstream by two stages of stators or straightening vanes. The upstream set of straightening vanes is highly cambered, but the downstream set is very lightly cambered. The 32 fan blades are made of fiberglass and epoxy resin utilizing a seven-spar arrangement. The straightening vanes, 23 in each stage, are of cast aluminum. The diameter of the fan is 17 ft and the hub-to-tip ratio is 0.7.

The shaft and fan is supported by two bearing rings mounted on pedestals in the nacelle, one ahead and one behind the fan. The upstream bearing ring is supported by 17 straight structural struts connected to the tunnel wall. The downstream bearing ring is supported by the downstream straightening vanes. Each bearing ring has a main lubrication system as well as an emergency lubrication system. In addition, each bearing ring is supplied with high-pressure oil for lift jacks. The high pressure pumps are interlocked with the main drive motor to prevent starting the main

motor unless pressure is being supplied to the lift jacks. Leakage of bearing oil is prevented by a reduction of pressure in the bearing boxes by vacuum pumps. Two single, straight, hollow struts, one immediately upstream of the 17 support struts and one immediately downstream of the downstream straightening vanes, are used to route the oil lines to the bearings.

Space and provision was made during design and construction of the tunnel for the addition of a second fan immediately upstream of the existing fan, between the support struts and the fan.

There are hatches on the top of the tunnel over the present and future hub locations to permit installation and removal of blades. The shed type structure shown on the top of the tunnel in figure 19(-) covers a handling frame for installation and removal of the blades. There is also a larger hatch in the bottom of the tunnel to permit installation and removal of the two hubs.

The blades are fixed to the rotor through special sockets which are bolted to the hub. The base of the blades is recessed in its socket through a slotted cutout running diagonally along the chord line of the blade and fastened to the socket with a single pin. Sufficient clearance between the blade tips and the tunnel wall is included to account for stretching of the blades during operation.

The rotor blade section varies from NACA 65-(11)15 at the root to NACA 65-(11)18 at the tip, and the solidity of the rotor varies similarly from 1.5 to 1. The blade section in the first stator varies from NACA 65-(8)12 at the root to NACA 65-(14)12 at the tip, and in the second stator similarly from NACA 65-(10)12 to NACA 65-(13)12. The solidity is the same for both stators, varying from 1.44 at the root to 1.00 at the tip. The axial velocity into the fan varies from an estimated 540 ft/sec at the root to 210 ft/sec at the tip. The design pressure ratio across the fan at 800 RPM is 1.17.

The first set of blades installed in the tunnel in 1952 were wooden and were destroyed in 1955. A second set of wooden blades were destroyed in 1960 and replaced by a third set of blades made of fiberglass and fabricated in-house. These "old" fiber glass blades were replaced in 1972 with a "new" set of fiberglass blades manufactured by the Brunswick Corporation. The tooling and molds used in fabrication of the "new" blades were saved and are currently stored in the back leg of the 8-ft. TT.

In 1975 a model balance failed and damaged about twenty seven of the "new" blades requiring reinstallation of the "old" blades. Seven of the "new" blades were beyond repair but the remaining twenty were repaired. In 1976, the twenty five good "new" blades were reinstalled along with seven of the "old" blades, leaving twenty five of the "old" blades as spares. Individual blades have been

damaged from time to time requiring removal and repair. In general, however, the fan used a combination of about twenty five of the "new" fiberglass blades and seven of the "old" fiberglass blades until early 1991.

In 1981, when the tunnel was modified for the Laminar Flow Control Experiment (ref. 6), all the blades were removed and repaired, and the leading edges were coated with an erosion protection material called silastic. At the same time, new fan blade retaining boxes constructed of AISI 4130 steel plate were installed. The old boxes had been in use about 20 years and a number had developed cracks at the blade retaining pin holes. These cracks had been repaired to prevent the occurrence of more serious failures. Since the new boxes were designed to fit the existing rotor hubs and fiberglass blades, there was little that could be modified dimensionally. However, close attention to metallurgy; heat treatment; stress relief; and minimization of stress concentrations by attention to fits, finish, and use of radii rather than sharp corners were expected to enhance the serviceability of the new boxes.

At the end of 1990, the "old" fiberglass blades had approximately 20,232 hours of run time, the "new" fiberglass blades approximately 9,046 hours, and the blade boxes approximately 1,973 hours. The fan shaft and hub had approximately 28,463 hours of run time.

In January, 1991, 15 blades were damaged due to the failure of a model and since that time the fan has used a combination of 14 "new" blades and 18 "old" blades. These 15 blade replacements do not have the same protective erosion coating on the leading edges as applied in 1981 and therefore may be more susceptible to damage.

Any imbalance of the fan and shaft during operation is detected by dynamic pickups which measure the vertical and horizontal RMS displacement of the shaft. The operating limits of such displacement has been established to be 0.0025 in. and an alarm is sounded when this limit is reached. Because of the weight of the shaft, the vertical displacement during operation is very small. Independent readouts of the displacement are located on the tunnel operator control console and in the "mezzanine" electrical control area. In January, 1989, as part of the restoration of the test section to its slotted configuration following the LFC Experiment, the fan and new blade boxes were dynamically balanced and the resultant horizontal shaft displacement measurements were as shown in figure 22. The fan was rebalanced following replacement of the 15 damaged blades in January, 1991 and the results are also shown in figure 22.

## Test Section

*General configuration.* The test section within the plenum is cantilevered from the tunnel shell at the upstream end and supported in the middle by six vertical columns (fig. 23(-)). The six columns are pinned at both ends to allow for movement of the the test section due to expansion and contraction with temperature. The contours of the contraction region of the test section are fixed and the test section joins the contraction region and diffuser with tight flange joints. The joints are reasonably smooth and air tight, producing no harmful disturbances. At the downstream end of the test section, between the constant-area circular section and the diffuser, there is a sliding expansion joint to accommodate differences in temperature between the test section and the outer shell of the plenum. The expansion joint is essentially a sealed gap with a sliding plate welded to the interior wall of the test section on the upstream side of the gap and free to slide over the downstream edge of the gap.

Because of the wall boundary-layer development, the aerodynamic throat of the test section occurs about 30 in. downstream of the geometrical throat. At the aerodynamic throat, which corresponds to the slot origin, the cross section of the test section is 85.51-in. square. After allowing for 8.55-in.-radius fillets in the corners, the cross section area is 50.3 ft<sup>2</sup>—equivalent to the area of a circle with a diameter of 8.01 ft. Although the slot origin is at the 50-ft station as far as the overall tunnel circuit dimension system is concerned, dimensions in the test section are normally referenced, for convenience, to the slot origin as station zero.

Wall curvature in the contraction region decreases gradually downstream until the curvature of the walls at the aerodynamic throat is zero and the slope of the wall surfaces with respect to the tunnel centerline is 5 minutes. Downstream of the slot origin the divergence of the solid side walls of the test section remains constant at 5 minutes. On the top and bottom slotted surfaces the slope gradually increases over the first 6 ft to 13 minutes and remains constant thereafter over the remaining 7 ft of the slotted test section and in the diffuser entrance section.

*Test section slots.* The top and bottom test section walls (floor and ceiling) each contain four equally spaced rectangular cutouts approximately 7.5 in. wide in which steel inserts are bolted to form the contours of the slots. (fig. 18). The slot contours are based on experience gained through the development of the slotted wall concept in the 8-ft TT and experimentation in the 8-ft TPT on different slot configurations. They are shown in figure 24 and identified as slot configuration 2f.

The open ratio of the slots, based on twice the width of the test section, increases rapidly from

zero at tunnel station zero (the slot origin) to 10 percent at the 42-in. station. It then decreases not quite as rapidly to an open ratio of about 4 percent at the 82-in. station and remains constant to about the 88-in. station. The rapid opening provides a rapid expansion of the flow and the closing counteracts this effect to prevent overexpansion in order to establish an uniformity of the axial flow distributions. Downstream of the 88-in. station, the slots again expand to 10-percent open ratio at the 108-in. station and remain a constant width to the 132-in. station. There is then a very rapid expansion to an open ratio of 20 percent at the 136-in. station. From the 136-in. station to the nose of the diffuser entrance flaps at about the 147.5-in. tunnel station the open ratio remains constant at 20 percent. The average open ratio from tunnel station zero to the nose of the diffuser entrance flaps is about 8.5 percent.

Since the slot openness varies along the test section, assigning a value for the average openness ratio is somewhat arbitrary and would depend on over what portion of the test section the average was calculated. If the average were weighted more toward the narrow slot region in the middle of the test section where a model would be located (between approximately the 70-in. and 120-in. stations), a more meaningful, effective average open ratio would be about 6.9 percent. Downstream of the nose of the diffuser entrance flaps, the open ratio remains constant at 20 percent to the 167-in. station. From the 167-in. station the slots diverge at  $6^{\circ} 15'$  until the slots come together at a point at the 246-in. station, 4 inches downstream of the test section access door (fig. 18(-)).

In the region of the test section where the slots are the widest, there is danger of injury due to personnel stepping through the slots, particularly when the diffuser entrance flaps are open. As a safety precaution, floor mats are normally placed over the slots when personnel are working in the test section.

*Test section windows.* The side walls of the test section contain 30 rectangular windows each about 19 by 19 1/2 inches. These windows, 15 on each side wall, are grouped in three horizontal rows of five windows and extend from the 22-in. station to the 150-in. station as shown in figure 16. The windows are made of 1.0-in.-thick optical plate glass refinished for use with the schlieren system. The description "refinished" indicates that the windows were removed from the test section and refinished by polishing with rouge after the original felt polished windows resulted in mottled schlieren photographs. Over the years some of the windows have become badly scratched and the least damaged ones are located in areas of the test section where schlieren photographs are most likely to be taken. Although not normally required to withstand large loads, the windows are capable

of withstanding a load of 90 psi. Four additional windows, two on each side, are provided in the diffuser entrance section. The two in the west side wall, the wall nearest the control room, are in the test section access door. The other two are in the East wall immediately opposite the access door. Most breakage of windows has occurred during window removal and replacement and there are currently no spare windows available.

There are also four small rectangular windows along the centerline of the test section in the floor and ceiling between the slots. Access to these floor and ceiling windows is through the test section support structure and is somewhat cramped but they do provide space for lights and cameras.

The test section windows are potted in metal frames with silicone rubber (RTV 88) so that the glass is isolated from the metal structure. As originally installed, the temperature characteristics of the mounting material around the windows required a temperature limit system which alarmed at 140° F tunnel stagnation temperature and shut the tunnel down at 160° F. The temperature characteristics of the potting material currently used are much better but the tunnel temperature alarm system, using two independent thermocouples mounted on the west wall of the contraction region, is still in operation.

*Test section flow angularity.* Measurements have indicated that before the installation of the screens and honeycomb there was about 0.2° downflow along the centerline of the test section for small models. Early flow surveys indicated two long, weak, counter-rotating vortices in the test section with downflow at the centerline and upflow at each side wall. The existence of such a pattern was supported by upright and inverted tests of large span models where the downflow in the center of the test section and the upflow near the walls tended to cancel and give an effective 0° flow angularity. It has been suggested that this double vortex originated at the approximately waist high protection screen immediately ahead of the cooling coils where the flow was forced to roll up toward the ends of the screen. The flow pattern in the test section since the installation of the screens and honeycomb in 1981 has not been established.

*but limited measurements made with models upright and inverted indicate flow angularity to be small, probably less than 0.05°.*

### Diffuser Entrance

The 8-ft-long diffuser entrance section, starting at the 156-in. station and ending at the 252-in. station, contains the approximately 98.5-in long diffuser entrance flaps which are located beneath the slots in the top and bottom walls (fig. 16). The diffuser entrance flaps are more commonly referred to as the "reentry flaps" since the air exits the test section over the upstream end of the slots and reenters over the downstream end, thus permitting continuous operation through transonic

still time?

speeds. The leading edge or nose of these flaps, located at the 147.5-in. station, can be rotated about a hinge line at the 250.4-in. station. The reentry flaps are positioned fully closed (leading edge positioned at the underside of the slot lips) for subsonic Mach numbers up to 0.95. Above  $M_{\infty} = 0.95$ , the flaps are progressively opened with increasing Mach number in order to flatten the test section Mach number distribution. Calibration of the test section includes optimization of the reentry flap leading edge position, as measured by the digital output of a datex encoder device, for each Mach number.

The approximately 6 ft by 7 ft hydraulically powered test section access door is also located in this section of the tunnel—in the wall nearest the control room (west wall)—between the 166 and 242-in. stations.

### Diffuser

The 8-ft-long diffuser entrance section (the downstream end of which is rectangular—95.1 in. high and 86.24 in. wide) is followed by a 4-ft-long diverging rectangular section between the 252-in. and 300-in. stations. The side walls of this section are parallel, but the top and bottom surfaces diverge  $4^{\circ} 46'$  with the horizontal plane of the tunnel centerline. The area divergence is the same as that of a conical diffuser with  $5^{\circ}$  included angle. This rectangular section is followed by a 9-ft-long transition section from rectangular to the constant area circular section. The transition section diverges with an equivalent conical expansion of  $4^{\circ}$  included angle. The constant-area circular section is 5 ft long and 114.44 in. in diameter. The remainder of the diffuser diverges with an included angle of  $6^{\circ}$ . The diffuser divergence is considered to be marginal as far as separation is concerned and experience indicates that there is some separation present in the diffuser. No definitive measurements have been made.

### Screens and Honeycomb

There are a honeycomb and five screens mounted perpendicular to the longitudinal axis of the tunnel in the 36-ft diameter settling chamber immediately downstream of the cooling coils and approximately 50 ft upstream of the test section slot origin. Figure 13 shows their location relative to the overall tunnel circuit and figure is a sketch of the general installation. The honeycomb was located as close as possible to the turning vanes at Ring D, and the first screen was located 30 in. downstream of the honeycomb. The five screens are located on 12-in. centers. The support structure around the perimeter of the honeycomb and screens is covered by a 10 in. deep fairing resulting in

a circular exposed area with 34 ft, 4 in. diameter.

The honeycomb has an open area of 95 percent with cells 3/8 in. across (referred to as square cell honeycomb) and 3 1/2 in. deep. It is made of 304 stainless steel with 0.006-in. wall thickness. The screens are 30 mesh, 304 stainless steel, with open ratios of 0.65. Wire diameter is 0.0065 in. Reference 6 discusses the design of the honeycomb and screens and reference 7 discusses how they were installed.

The screens were designed to have a maximum deflection of 6 in. in the center with a total pressure drop across the five screens of 12.5 psf (2.5 psf each). The allowable deflection is based on the strength of the brazed joints in the screens which are only 75 percent as strong as the screen wire itself. During tunnel operation the difference in pressures measured by stagnation pressure probes immediately upstream of the honeycomb and immediately downstream of the screens is monitored and loads on the screens are restricted to a 12.5 psf pressure drop. Measurements have indicated the pressure drop across the honeycomb to be practically negligible.

### **Safety Valves**

There are two types of safety valves in the tunnel circuit to protect the tunnel against overpressure. First, there are three safety relief valves set for 15 psig, each capable of handling 5 000 cfm of air at 2 atm absolute pressure assuming exhaust to atmospheric pressure. Second, there is a rupture disk set for 17 psig capable of exhausting approximately 97 lb/sec of air.

There is a third type of emergency protection valve which is remotely operated from the tunnel operator console in the control room and designed to vent higher pressure stagnation air ahead of the cooling coils to the lower pressure air in the plenum surrounding the slotted test section. This valve is referred to as the "flutter valve" and can be used to quickly drop the Mach number in the test section in case of unstable model motion or flutter.

### **Freestream and Reference Conditions**

Reference freestream stagnation pressure is currently measured with a sonar-sensed mercury manometer using a forward facing tube (referred to as  $H_3$ ) mounted on a strut on the floor of the settling chamber approximately 1 ft. downstream of the last screen (fig. 18(-)). A second stagnation pressure tube on the same strut ( $H_4$ ) is used as an independent pressure source for pressure instrumentation referenced to freestream stagnation pressure. Two additional stagnation pressure tubes are mounted on the upstream face of the honeycomb, approximately 5 ft above the

floor of the settling chamber and 8 ft to either side of the vertical centerline of the tunnel. One ( $H_1$ ) is used in conjunction with the stagnation pressure source downstream of the screens ( $H_4$ ) to measure the stagnation pressure drop across the honeycomb and screens. As previously discussed, this pressure drop is routinely monitored as a safety precaution against overloading the screens. The second upstream stagnation pressure tube ( $H_2$ ) is a duplicate of  $H_1$  and available as a spare pressure source.

Reference static pressure in the plenum is also measured with a sonar-sensed manometer using a small pressure chamber with a perforated, shower-head shaped cover mounted on the plenum wall near the control room observation window. This measured static pressure is used along with the measured freestream stagnation pressure to compute a Mach number referred to as test chamber or plenum Mach number which is calibrated against the average freestream Mach number measured along a centerline probe in the test section. Once the calibrated freestream Mach number is determined from calibration data, a freestream static pressure is computed.

This computed freestream static pressure is also used to correct various pressure-measuring devices which use plenum static pressure as a reference. A second shower-head plenum static pressure orifice mounted near the first one is used as the pressure reference source for pressure instrumentation.

Freestream temperature is measured with a chromel-alumel thermocouple mounted on the upstream face of the honeycomb in the center of the settling chamber. In all there are twenty-five thermocouples mounted on the honeycomb to measure the temperature distribution across the settling chamber behind the cooling coils. Nineteen are distributed along the horizontal centerline plane and three are located above and below the horizontal centerline along the vertical centerline plane. In addition, there are seven thermocouples mounted on the upstream face of the cooling coils at corresponding locations to those on the honeycomb.

Before installation of the honeycomb and screen, stagnation pressure and temperature were measured with probes mounted on cross wires in the center of the 36-ft-diameter settling chamber. Since these wires would generate vorticity in the test section and defeat the purpose of the honeycomb and screens, the cross wires were removed at the beginning of the LFC Experiment.

Tunnel humidity is monitored with an opened ended tube, located on a floor mounted strut immediately upstream of the honeycomb, that collects samples of the freestream air. This probe is connected to a dewpoint hygrometer located in the control room and used to measure freestream

dewpoint as an indicator of when condensation would be expected to occur.

As mentioned above, freestream Mach number in the test section is obtained by first calculating a Mach number based on measured values of the freestream stagnation pressure and the static pressure in the plenum surrounding the test section. Tunnel empty calibration data that relates plenum Mach number to the average freestream Mach number in the test section is then used to determine freestream Mach number.

## Descriptions of Auxiliary Systems and Equipment

### Diffuser Spoilers

Just downstream of the reentry flap hinge, and somewhat upstream of the diffuser transition section, spoilers are mounted on the tunnel floor and ceiling walls (figs. 16 and 18(-)) with their hinge line located at the 255-in. station. These spoilers are simple flat plates, completely span the width of the tunnel, have a streamwise chord of 24 in., and are referred to as "diffuser spoilers". They can be driven remotely through an angle range of about  $-3^\circ$  to  $30^\circ$  (relative to the tunnel horizontal centerline) and are used with a semi-automatic servo system to provide rapid Mach number control to compensate for test section blockage as models are driven through an angle-of-attack range. When used as a Mach number trim device, tunnel RPM is set high enough to achieve the desired Mach number with the model in the center of the test section and the diffuser spoilers slightly into the flow. As the angle of attack, and thus model blockage, varies, the diffuser spoilers move in and out of the flow to hold the test section Mach number constant. Generally, only two to three degrees of movement are needed to trim the Mach number for conventional size models. Care must be taken to avoid large flap deflections, greater than about  $10^\circ$ , which would separate the flow in the diffuser. Investigations have indicated that, with proper angular limitations, the diffuser spoilers have no discernible effect on model base pressure or afterbody drag.

The spoilers may also be used as a manually operated safety device to quickly drop the Mach number in the test section if necessary. Rapid manual movement of the spoilers  $25^\circ$  into the flow drops the freestream Mach number from 0.90 or 1.20 to 0.50 in about 30 seconds.

### Cooling Equipment

Cooling of the tunnel air, the main drive, all auxiliary equipment, and the 100 000 cfm compressors is accomplished by circulating cooling water from the cooling tower located across

the parking lot opposite the northeast corner of Building 641. This induced draft cooling tower is constructed primarily of redwood and designed to lower the temperature of approximately 13 000 gpm from 110 ° F to 90 ° F. It is estimated that, due to age and deterioration, the cooling tower is currently operating at only about 75 percent efficiency.

Water to be cooled is pumped to the top of the tower and discharged in a spray in the distribution chamber. As the water falls into the basin in the bottom of the tower, the drops are further broken up for greater surface exposure by layers of grid decks. The water descends through a stream of air being drawn in at the bottom of the tower by fans located in the top of the tower. As the air is drawn upward and exhausted through the fan shrouds, it accumulates heat from the water by evaporation.

The cooled water from the cooling tower is gravity fed through a 36 in. underground pipe to distribution pumps located in a pit near the 100 000 cfm compressors on the first floor of Building 640. There are four pumps that force the water through various distribution lines and back to the top of the cooling tower through a 30 in. underground pipe. Two of the four pumps, each of 3 500 gpm capacity, supply cooling water to the finned cooling tubes across the northeast corner (Ring D) of the tunnel. A third pump of 2 500 gpm capacity supplies cooling water for the main motor, for the control equipment, for the compressors, and for the refrigerator units. A fourth pump, having a capacity of 3 500 gpm, is used for supplying cooling water for the two 100 000 cfm boundary layer removal compressors. The 36-in. inlet and 30-in. return pipes to and from the pumps are large enough to carry 24 000 gpm of water.

Cooling of the tunnel air is accomplished by means of coils across the north-east corner (Ring D) of the tunnel. Although referred to as cooling coils, they actually consist of eight banks of inverted U-tubes arranged and supported so as to form a uniform screen across the elliptical section of the tunnel formed by the intersection of two circular sections 36 ft in diameter. There are 1420 tubes or 710 U's. The tubes are seamless drawn cupronickel 90/10 composition with 1-in. outside diameter and 2-1/4 in. circular fins, 0.014 in. thick, spaced 1/8 in. apart. Cooling water is pumped to the top on one side of the U and falls back down the other side so that the cooling water makes a double passage through the tunnel. The eight supply valves to the cooling coils are normally set fully open and the eight return valves are normally set about 30 percent open to insure that the cooling coils are filled with water.

The coils are designed to continuously remove the heat equivalent to 25 000 hp. The water

temperature rise across the coils is approximately 20 ° F and raises the 90 ° F water supplied from the cooling tower to about 110 ° F. The maximum quantity of water supplied to the tubes is approximately 6 600 gpm and the mass flow of air through the bank of tubes at a stagnation pressure of 1 atm is about 2 442 lbs/sec. This mass of air is cooled approximately 30 ° F to affect the necessary heat removal. Depending on how much care is exercised in controlling the circulation to the eight individual banks of tubes, the temperature variation across the downstream face is generally maintained at less than 5 ° . With one atm stagnation pressure in the tunnel and maximum volume flow the power loss in the cooling coil is less than 750 hp.

The cooling water can be recirculated through the pumps, instead of being returned to the cooling tower, by means of a by-pass valve <sup>(N-105)</sup> the operation of which can be preset to maintain, within the capacity of the cooling system, a constant pre-determined temperature in the tunnel. The temperature range at which the tunnel air can be maintained varies throughout the year depending on test conditions and outside ambient temperature. An operating range between approximately 100 ° and 120 ° F is possible over most of the year and 120 ° F is usually quoted as the standard tunnel operating temperature.

In order to prevent corrosion and deposits in the piping circuits and in the cooling tubes, the water is chemically treated to deposit a thin easily-removable protective coating on the water side of the tubes. The small building which houses the treatment equipment is located at the inland base of the cooling tower.

In order to protect the tower against fire damage, a deluge system as well as an automatic sprinkler type wet down system for the fan platforms were installed in the mid 1970's. The deluge system is housed in a small building next to the treatment house at the base of the tower.

The tower basin capacity is approximately 125 000 gallons but the normal water level is maintained at approximately 60 000 gallons. In the mid 1970's, the leakage rate was estimated to be approximately 440 gal/day (24 hour day). Under normal tunnel operating conditions with an average flow of 10 000 gpm a maximum of about 235 gpm of replacement water is required to compensate for evaporation and windage.

### Drying Equipment

Provision is made to dry the air in the tunnel circuit to prevent both global condensation in the test section and local condensation in pockets of supersonic flow on the surface of models by circulating the air through a two-unit dryer with the 10 000 cfm compressor. The air can be dried

to a dew point of  $-40^{\circ}\text{F}$  and one dryer unit may be in operation while the other is being reactivated on an 8 hour reactivation cycle. The dryer uses silica gel as a desiccant and each unit has a capacity of 2 500 ft<sup>3</sup>/min at pressures up to 4.0 atm. The air output from the dryer has a dew point not exceeding  $-70^{\circ}\text{F}$ . A filter prevents dust from the desiccant from entering the tunnel. The dryers also include pre-coolers and after-coolers.

Studies have indicated that condensation effects on model data are not generally discernible until condensation is visible in the test section and, normally, dew point temperature is maintained between approximately  $-10^{\circ}$  and  $+20^{\circ}\text{F}$  for most models and operating conditions.

With the use of the air driers the relative humidity in the test section can be maintained at approximately 38 percent up to Mach number of 1.20.

As will be discussed in more detail in a following section, there is a second, more indirect method of introducing dry air into the tunnel. When pumping the tunnel circuit up from below atmosphere stagnation pressures or when maintaining above atmosphere stagnation pressures using the 10 000 cfm compressor, outside air is pumped into the tunnel and dried by circulating through the silica gel dryers. A 350 psi compressor (the Joy compressor) remotely located about a block away in the East Area Compressor Station (Bldg. 646) and which has its own dryers, may also be used to introduce dry, high pressure air into the tunnel. This is not done on a routine basis, however, since it requires personnel outside the 8-ft TPT facility to operate the compressor and that valves on the roof of Bldg. 640 be opened.

### Compressors

Several different size compressors are available for evacuating or pumping air into the tunnel, for maintaining the tunnel stagnation pressure against circuit leaks, and for pulling the boundary layer off the test section walls and through the slots. These compressors may be used alone or in combination depending on the situation. The compressors and auxiliaries must be started from the first floor of building 640, but operating controls are located in the second floor control room. Special controls for the compressors include controls to limit the power input, to pre-determine the desired mass flow, to prevent the compressors from surging, and to prevent valves from two or more air circuits to be opened at the same time.

*10 000 cfm compressor.* The primary compressor used to control stagnation pressure and which is also used to circulate air through the dryers is a 1 800 hp, 10 000 cfm compressor with a compression

ratio of 4 to 1. It is equipped with an after-cooler and with a pre-cooler which is automatically bypassed when temperature of the entering air is 32 ° F or less. It is also equipped with a manually controlled back-pressure valve following the refrigerated cooler and the dryer. Through this back-pressure valve the air which has been dried at pressures up to 4.0 atm expands into the tunnel. This compressor is adequate for use with 2 atm operation of the tunnel and is capable of pumping sufficient dry air into the tunnel to raise the pressure inside the tunnel from 1.0 to 2.0 atm in about 30 minutes. Similarly, the tunnel can be evacuated to approximately 1/4 atm pressure in about 40 minutes. There is an operating procedure whereby the 10 000 and 100 000 cfm compressors can be operated in series and the tunnel evacuated below 1/4 atm to near 1/10 atm. Such a procedure is complicated, difficult to control, and not normally used.

When initially installed, there was a piping circuit from the 10 000 cfm compressor to the 8-ft TT. Air was pulled from the tunnel through a floor penetration and through an underground pipe beneath the courtyard between the two tunnels. The underground pipe is still in place but has been cut and blanked off immediately inside Bldg. 640.

*100 000 cfm compressors.* The 100 000 cfm compressor system consists of two large compressors manufactured by the Elliott Corp. and includes precoolers, aftercoolers, and piping for three different air removal circuits. Each compressor has a rating of 96 000 cfm inlet volume when operating at a pressure ratio of 4 to 1. As mentioned previously, these compressors are referred as the "100 000 cfm compressors" or the "Elliotts". They are of the 3-stage centrifugal type and each unit is coupled directly to a 3 600 RPM synchronous motor. The motors are each rated at 4 000 hp for continuous operation and may be operated at 5 000 hp overload conditions for a 30 minute period. The acceptance tests of these motors indicated that the motors may be continuously operated above their rated horsepower—possibly as high as 6 000 hp—without overheating the motor windings.

As indicated, the 100 000 cfm compressors are plumbed into three different air circuits (fig. 15(b)). One circuit is used to overcome solid blockage in the 8-ft TPT test section associated with large models at high Mach numbers by pulling the test section boundary layer through the slotted floor and ceiling. It connects the suction side of the compressors to the test section plenum through a tunnel shell penetration in the upper southwest quadrant of the plenum. To conserve mass flow around the tunnel circuit, the discharge side of the compressors return the air to the tunnel circuit through the hollow turning vanes in the southeast corner (tunnel Ring A) immediately upstream of the main drive fan. At  $M_\infty = 1.3$ , early compressor calibrations indicated that about 2-1/2 percent

of the main air stream was removed by the compressors. This circuit may also be used for accelerated evacuation of the tunnel circuit by exhausting the air pulled from the plenum to the atmosphere.

A second circuit was used for plenum suction in the 8-ft TT while it was still in operation. The test section boundary layer pulled through the slots passed through four penetrations in the igloo test section plenum—two in the ceiling and two in the floor. The air passing through these four penetrations went to the compressor through an overhead pipe above the courtyard between the two tunnels. This overhead pipe was removed in 1981 to permit fabrication of a truss system for installation of screens in the settling chamber for the laminar-flow-control experiment (ref. 7). In this circuit the discharge air from the compressors was dumped to the atmosphere instead of being returned to the tunnel circuit and the air pumped out of the 8-ft TT was replaced by air which entered the tunnel through the heat exchanger. The last run of the 8-ft TT utilizing boundary layer control was made in late 1960.

The third piping circuit was used to drive the research facility on the third floor of Bldg. 640. The suction side of the Elliott compressors was connected to the downstream end of the facility and the discharge of the compressors to the upstream end. The 8-ft TPT and the facility on the third floor could have conceivably been run at the same time but because of various operational, procedural, and safety concerns this was never done. Although the research facility has been removed, the piping circuit is still in place.

There are two isolation valves (identified as valves SP and DP) in the connecting piping between the now nonexistent BARF on the third floor and the 8-ft TPT plenum. Safe operating procedures required an interlock system to insure that these valves were closed when the 100 000 cfm compressors were being used to power the BARF in order to prevent accidental pressurization or evacuation of the 8-ft TPT plenum. They are permissive valves—either open or closed—rather than modulating valves and a bucket truck must be used to operate one of them since it is located on top of the long back leg of the tunnel. 2

There are two 24-in. diameter, 19.25 psi rupture disks to atmosphere located near valve DP to protect the compressors against accidental overpressure in the case of failure of valve DP to function properly.

*3 000 cfm compressor.* When originally installed the air removal system included a 3 000 cfm compressor with a pressure ratio of approximately 1.3 to 1—essentially a blower. This compressor was used to circulate the air in the 8-ft TPT or the third floor hypersonic facility through the driers.

The suction side of the compressor was connected to the discharge side of the # 2 Elliott compressor and the discharge side was connected to the 8-ft TPT drying system. Dry air was piped back to the hypersonic facility through a 6.0-in. line which connected the drying system to the hypersonic air removal system piping circuit.

This low pressure ratio compressor was removed during the laminar-flow-control experiment and replaced with a higher pressure ratio 2 000 cfm compressor discussed below.

*2 000 cfm compressor.* In 1984, a 2 000 cfm vacuum pump was installed in place of the 3 000 cfm blower and connected into existing tunnel piping to maintain stagnation pressure against circuit leaks when the tunnel was operating at low stagnation pressures. The vacuum pump was required because the 10 000 cfm compressor which normally maintains stagnation pressure was dedicated to model suction for the laminar-flow-control experiment. The pump is a single stage pump of the basic rotary lobe design, equipped with a splash oil lubrication system. Clearances around the rotating parts are sealed and cooling of the pump is achieved by direct injection of domestic water into the flow stream. The maximum recommended water flow to the pump was 24 gpm but the maximum measured flow to the pump was 15 gpm so that no restriction was required in the piping. The pump includes a silencer at the exhaust which acts as a sound suppressor and also recovers injected water which is discharged into a storm drain in the floor. Since the exhaust air contains both water and oil, it is not returned to the flow circuit but is piped to an atmospheric exhaust above the roof at the rear of Building 640. To prevent damage to the pump when operating the tunnel above atmospheric pressures, a manual chain operated valve on the intake side of the pump is procedurally closed. This valve was used with the old 3 000 cfm blower and referred to as the "isolation valve".

*350 psi compressor.* There is a 15 418 cfm Joy compressor with dryers located in the East Area Compressor Station (Bldg. 646) capable of producing dry 350-psi air and connected to the Low Turbulence Pressure Tunnel in Building 582 with a 6-in. pipe which runs along the roof of Building 640. There is a 6-in. pipe teed to this connector pipe to supply high pressure air to a powered engine system located in the plenum of the 8-ft TPT. This high pressure supply line to the powered engine system penetrates the plenum wall through the floor. Another pipe, 2 in. in diameter, is teed from the powered engine supply line and connected to the 12 in. 10 000 cfm compressor inlet line so that high pressure air can be introduced directly into the tunnel circuit if the 10 000 cfm compressor is not operating or indirectly through the 10 000 cfm compressor itself.

*Vacuum pumps.* Also during the laminar-flow-control experiment, two 350 cfm Stokes vacuum

pumps were installed in 1987 on the first floor behind the 2 000 cfm compressor to supply additional suction for the laminar-flow-control airfoil. These two pumps were independent of each other and pulled air from the plenum through two penetrations in the large hatch in the lower east quadrant of the plenum. The exhaust air was vented to atmosphere above the roof in the rear of Building 640. Installation included oil mist separators which were simply large cannisters with baffles which slowed the exhaust air so that lubricating oil would separate out and flow back to the pump. Not all the oil was separated out, however, and a small amount was released in the exhaust air. At the end of the laminar-flow-control experiment in 1988, the two vacuum pumps were removed to be used in another facility but the piping for the pumps was left in place.

### Powered Engine System

A powered engine simulation module for specialized testing (jet engine simulators, for example) with valves to distribute high pressure air from the 350 psi compressor was installed in 1978 and is located on the floor of the plenum (fig. 25). The module contains three 2-in. and one 3-in. hand operated gate valves with 6-in. and 2-in. remotely operated dome loaded regulating valves. The remote controls for this powered engine module are located on the test operator console panel in the control room. The 350 psi compressor is capable of delivering 17 lb/sec flow to this module at a pressure of 350 psi.

Before the installation of the pipe line from the 350 psi source, there was a bottle field under the southwest corner of the tunnel which supplied nitrogen gas to the test section at a pressure of 5 000 psi for powered engine simulation. This bottle field, which may be seen in the photograph of figure 8, was removed in 1986.

### Flow Visualization System

*Schlieren system.* The schlieren apparatus is an off-axis system with 25-in. parabolic mirrors. The position of the knife edge and location of the system as a whole are variable by remote control from the control room. The system is beam mounted and attached to one of the two cranes in the ceiling of the test section plenum. Its location is remotely variable, both vertically and horizontally, parallel to the tunnel axis and in yaw in the horizontal plane. A 70 mm Hasselblad camera is used to record schlieren observations and a 3 digit BCD code is transmitted to the data acquisition system for photo identification. A movie camera can be used in place of the still camera if desired. Continuous schlieren observation is available by use of a closed circuit television system.

*Vapor screen flow visualization system.* The laser vapor screen (LVS) system is used to visualize off-surface flows about models. It is a diagnostic tool that provides a description of vortex-dominated flows and flow-field interactions that can be correlated with quantitative measurements such as model forces and moments and surface pressures. Basically, the system works by injecting water into the tunnel circuit to increase the relative humidity and projecting an intense sheet of laser light into the test section to illuminate the condensation patterns about the model. At subsonic speeds the water vapor present in the freestream condenses in the vortex flows and appears as bright regions surrounded by a dark background. At transonic speeds, the water vapor condenses in the freestream and the vortical flows typically appear as dark areas with a light background. The light source is provided by a 6-watt, continuous-wave argon-ion laser located in the upper observation room. The laser beam is steered into the plenum and to the top of the test section through a 60-ft fiber optic cable having a 200-micron diameter core. The laser lightsheet is generated within an optics package positioned on the top of the test section and a mirror directs the lightsheet to the model. The intensity, orientation, location, divergence, and thickness of the lightsheet are remotely controlled. Deionized water is pumped from a 150-gallon reservoir located in the third floor observation room and injected through the tunnel ceiling into the flow at the diffuser entrance. The laser-illuminated flow fields are observed through the test sections windows using color pan-tilt video cameras mounted outside the test section and by a camera mounted behind the model on the main support strut, looking upstream. A video station is located in the control room to view, document, analyze, and edit the results, and to generate real-time color video prints, or postprocess selected videotape images.

Following use of the laser screen system it is often necessary to dry the air to reduce the amount of moisture in the circuit.

*Surface shear flow visualization.* There is presently no developed procedures or equipment available for viewing or evaluating surface shear stresses. Because of possible contamination of the honeycomb and screens, the use of fluorescent oil for flow visualization is not encouraged.

## **General Operation**

### **Operational Controls**

There are two control rooms associated with the operation of the facility. One contains the electrical controls for the main drive system. It is located in the mezzanine area and referred to as "the mezzanine". The second control room is located on the second floor and contains enough

duplicate main drive electrical controls to change Mach number by varying fan RPM as well as controls for all the other facility test systems. This second room is the primary control room for the facility and is referred to as "the control room".

Controls for the various test systems are located on a console beneath the large observation window (fig. 20). Status lights on the console to indicate dangerous operating conditions in the electrical systems are duplicated in the mezzanine. Operational controls for auxiliary equipment and annunciator lights for warning of overall operational dangers are located on a vertical graphic panel at the rear of the control room opposite the control console. This control panel is referred to as the "graphic panel" because the auxiliary equipment, piping circuits, various control valves, and status lights are graphically displayed on a large vertical schematic diagram of the tunnel circuit. Controls for the 100 000 cfm Elliott compressors are located on the left of the graphic panel.

### Operating Personnel

Five qualified technicians are required to operate the 8-ft TPT. The five are: (1) a tunnel operator who controls the main drive RPM, the reentry flaps, and the diffuser spoilers; (2) a test operator who operates the computer data acquisition system and the model attitude control system and records the data; (3) a graphic panel operator who controls most of the facility auxiliary systems and equipment; (4) an equipment operator who starts the auxiliary equipment and who makes periodic equipment checks during the time that the tunnel is running; and (5) an electrical operator who controls the electrical equipment associated with the main drive. The electrical operator is located on the mezzanine and the other four operators are located in the control room.

These operators must have an adequate knowledge of the various systems, appropriate training, and demonstrated ability to satisfy the task requirements associated with the particular systems. Generally, facility technicians are cross trained and can operate more than one system.

*Tunnel operator.* The "tunnel operator" sits to the right of the control console when facing the plenum observation window where the various tunnel main drive controls are grouped. Primary duties include coordinating with the electrical operator on the mezzanine and with electrical power dispatchers; controlling the main drive RPM and diffuser spoilers and, thus, the Mach number in the test section; setting reentry flap position; monitoring the status of various high pressure and vacuum pumps associated with the main drive; and monitoring the vibration of the main drive shaft.

There are visual and audible alarms or annunciators lights to warn of excessive heat in the tunnel or in various bearings or in case of failure of oil supply to the main bearings. There is also

an emergency stop button on the tunnel operator control panel which interrupts power to the main drive and allows the fan to coast down. Under tunnel-empty emergency stop conditions, starting from  $M_{\infty} = 1.20$  (830 RPM) and  $p_{t,\infty} = 1\ 000$  psf, RPM drops to about 400 in 30 seconds, to about 50 in 4 minutes, and to "motor at rest" in 12 minutes.

*Test operator.* The "test operator" sits to the left of the control console where the controls for various test parameters, cameras, lighting, schlieren, television monitors, powered engine equipment, scanivalves, and data acquisition are located. Primary duties include coordinating with the tunnel and graphic panel operators to insure that tunnel test conditions are properly controlled, setting model test conditions, acquiring data, and keeping records of test conditions and events.

*Graphic panel operator.* The "graphic panel operator" station is located immediately in front of the graphic panel and forms a triangle with the tunnel and test operators. Primary duties include operation of temperature control equipment, operation of all drying equipment, and operation of all compressors including the Elliotts.

*Equipment operator.* The "equipment operator" is responsible for the startup of all auxilliary equipment associated with tunnel operation. Duties also include making periodic checks of all auxilliary equipment during the time that the tunnel is running to ensure proper equipment operation. In 1989, because of staffing limitations, it was necessary to create two qualification levels for equipment operator. The standard operating procedures were changed to allow an equipment operator with relaxed qualifications to perform periodic equipment checks without being fully qualified to start the auxilliary equipment.

*Electrical operator.* The "electrical operator" is responsible for startup and operation of electrical equipment and controls associated with the main drive system.

### **General Sequence of Tunnel Operation**

Pre-startup procedures for the tunnel include starting all lubricating equipment, cooling water pumps, compressors, and auxiliary pumping equipment and taking wind off zero data readings. Before starting the main drive motor, the humidity in the circuit is checked by means of an automatic dewpoint recorder. If drying is required, it may be done before main drive startup. If the desired tunnel stagnation pressure test conditions are to be below atmospheric pressure, tunnel pump down may be initiated before the required humidity is reached since evacuating the tunnel tends to reduce

the dewpoint. Tunnel pump down is also initiated before main drive startup to conserve energy if stagnation pressure test conditions are expected to be below 1.0 atm. Also, if test conditions include Mach numbers high enough to require the main drive to go through synchronous speed, the facility operating procedures require that stagnation pressure be at approximately three-quarter atmospheric pressure to reduce loads on the motor.

After all auxiliary equipment is started and appropriate levels of humidity and stagnation pressure are reached the electrical equipment is started by synchronizing the motor-generator sets. This takes about five minutes, after which the main drive motor may be started. Actual startup of the drive motor requires simultaneous activation of start switches in the mezzanine and control room. Acceleration of the main drive motor is controlled by regulating the frequency of the motor-generator sets. Final adjustments are then made to stagnation temperature and pressure, humidity, and Mach number to establish the desired test conditions.

After the main drive is started, the tunnel operator drives the fan to about 660 RPM where the Scherbius machinery automatically starts and drives the RPM to about 672. At this point the tunnel operator regains control and drives the RPM to around 700. The Kraemer-Scherbius control system does not permit operation at or very near the 720 RPM synchronous speed of the main motor, because at that speed the rotation speed of one of the machines in the Kraemer system is reduced to zero. Operation of the motor at speeds between 715 and 725 RPM is therefore prohibited and is prevented by automatic controls in the speed-control machinery. Between 700 and 708 RPM the normal operating procedure is for the tunnel operator to turn speed control over to the electrical operator on the mezzanine who makes fine adjustments to the electrical equipment so that transition through the 720 RPM synchronous speed may be made smoothly. Once the drive equipment synchronizes and RPM reaches about 725, control is returned to the tunnel operator. In addition, there is a rough spot in the drive control between 820 and 824 RPM which is usually "run through" without stopping.

At the end of a run, the main drive speed is reduced to approximately 50 RPM at which point the power is dropped to the main drive. The power to the motor generator sets is then dropped. Often, the tunnel is allowed to idle at low RPM for a short period of time before dropping off line in order to reduce the air temperature in the circuit and make it more comfortable to work in the test section. As noted earlier, it is also often necessary to allow time for drying the air in the circuit after using the laser screen flow visualization system.

## Equipment Checks

Facility operating procedures include a comprehensive system of equipment checks before, during, and after each run. These checks are documented on check list sheets and normally maintained as part of facility records. There is also a regularly scheduled "Monday Morning Check" during which critical instrumentation and equipment is inspected and checked. This Monday Morning Check usually takes about two to three hours. In addition, there is a three week annual maintenance shutdown for major maintenance of all primary and auxiliary equipment.

## Support Hardware

### Main Support System

The main model support system for the 8-ft TPT, shown in figure 18(-), is a motor-driven arc sector which can be moved axially about 6 ft, and has a variable-rate angle of attack drive. The center of rotation of the arc sector is 180 in. upstream of the arc sector itself. Several different length extensions are available which may be used to lengthen or shorten the main sting. Load limits for the main support system have, in the past, been quoted to be 4 000 lbs of normal force, 400 lbs of drag force, and 400 lbs of side force applied at the center of rotation.

A more recent stress analysis, performed in 1990, indicated that the base component of the main support strut and the arc sector are capable of supporting from -4 000 to +6 000 lbs maximum lift, 1 000 lbs maximum drag, 1 000 lbs maximum side force, and 7 500 in. lbs maximum rolling moment acting simultaneously at the center of rotation. Model loads would have to be less than this to account for any extra moments generated by placing the model ahead of the center of rotation. Also, reduction in these loads would be required if more stringent restrictions were imposed by weaker support equipment upstream of the base.

The axial travel of the center of rotation is from about the 122-in. station to the 195-in. station. Controls to move the main sting axially are located both in the plenum beneath the test section and on the control console in the control room. If guy wires are not attached the main sting can be moved while the tunnel is in operation, but it is not considered normal practice to do so.

The basic angle of attack range of the main support sting is from about  $-11^\circ$  to  $+14^\circ$  with angle of attack drive rate varying from zero to about  $40^\circ$  per minute. Various angular couplings or knuckles may be used to shift this angle of attack range. These coupling may also be used to offset the model laterally to obtain fixed sideslip angles

Since models are normally forward of the arc center of rotation, the model nose approaches the tunnel ceiling as the model is rotated to high angles of attack with potential for aerodynamic interferences due to wall proximity. There is limited support hardware available to offset the model vertically from the centerline so that the model does not approach as close to the ceiling at the positive end of the angle of attack travel of the support strut.

Model angle-of-attack movement in the negative direction is achieved by lifting the arc sector with a motorized drum on the top of the test section attached to a cable running down the downstream edge of the arc, attached to the bottom. Movement in the positive angle-of- attack direction is achieved by releasing tension on the cable and allowing the arc sector to move downward under its own weight.

### **Motorized Yaw Mechanism**

In addition to fixed couplings, a motorized yaw mechanism which permits remote controlled yaw angle variations for standard size models is also available. This yaw mechanism has a  $7.5^\circ$  angle of attack offset built in and provides for yaw angle variations of approximately  $\pm 7^\circ$ .

### **Guy Wires**

There is provision to attach guy wires to the model support strut to absorb side loads and to reduce the effect of model dynamics on the main support system. The usual guy wire configuration is two horizontal wires fastened to attachment points on the model support system at the center of rotation. The wires pass through the test section wall at the 161.5-in. station and attach to tensioning pulleys outside the test section. Locating models in the calibrated region of the test section usually results in the guy wires being swept relative to the flow. There is also provision for using four crossed wires in a X-configuration.

## **Model Information**

### **Model Size and Strength Requirements**

Acceptable model size is governed primarily by the Mach number desired, although maximum lift and other aerodynamic characteristics of the model may not be ignored. Experience has indicated that, as an example, fairly large model ( $S = 2.0 \text{ ft}^2$ ,  $b = 50 \text{ in.}$ , and  $\ell = 60 \text{ in.}$ ) may be accommodated if the highest test Mach number is restricted to approximately 0.95 or below. For this case, the

model frontal area should be kept to a value lower than about 1/2 percent of the test section area which is 50.3 ft<sup>2</sup> at the slot origin.

For tests through the transonic speed range, experience indicates that the maximum allowable model size is reduced considerably ( $S = 1.0$  ft<sup>2</sup>,  $b = 24$  in., and  $\ell = 35$  in.). The model frontal area should be less than about 1/4 percent of the test section area. Even for this case, however, questionable results could be obtained at, or near, sonic speeds ( $M_\infty = 0.98$  to  $1.02$ ) (See ref. 10).

A simple indication of when wall interference effects would be expected to appear may be obtained by finding the Mach number corresponding to

$$\frac{A}{A^*} = 1 + \frac{\text{model frontal area}}{\text{test section area}}$$

For example, for a model with a ratio of frontal area to test section area of 0.005,  $A/A^* = 1.005$ , and wall interference would begin to appear at a freestream Mach number of about 0.92.

In addition, transonic results may be affected by shock reflection. Therefore, depending upon model size, angle of attack range, and model vertical position in the test section, testing should not be conducted at Mach numbers slightly above sonic speeds where reflected shock waves would impinge on the model.

Models and test equipment must meet requirements detailed in the Langley Wind-Tunnel Model System Criteria Handbook. This document sets forth criteria for the design, analysis, quality assurance, and documentation of wind-tunnel model systems to be tested at the Langley Research Center and is incorporated into the Langley Safety Manual's "Facility Safety Standards" section. The criteria and requirements contained in this document are intended to prevent model system failure and/or facility damage and are mandatory for model systems to be tested in the 8-ft TPT. For models and sting supports not designed and constructed at the Langley Research Center, it is necessary to demonstrate either through a stress analysis report that satisfies the Model System Criteria Handbook, or by static loading, that the critical components have the required safety factors—three based on yield or four based on ultimate.

### Model Stings

The facility has an inventory of approximately 25 model stings of varying geometry and load capability. The standard downstream end of facility stings is a tapered female fitting with a maximum diameter of 2.25 in. and a taper of 1 in. per ft. Several adapters are also available to adapt the main support system to model stings from other Langley facilities such as the 16-ft.

Transonic Tunnel, the High Speed 7- x 10-ft. Tunnel, the Unitary Plan Wind Tunnel, and the National Transonic Facility.

*Sting selection.* The selection of a sting for a particular model should include consideration of possible sting/model interference effects due to sting geometry. Several references useful in sting selection are available (refs. 11 and 12, for example). Sting safety requirements parallel those of model requirements, that is, a safety factor of three based on yield or four based on ultimate.

*Sting divergence.* Sting selection or design shall also consider the possibility of aeroelastic divergence. Briefly, divergence will occur when the slope of the model normal-force versus angle-of-attack curve equals the reciprocal of the sting deflection constant. The required criterion for testing in the 8-ft TPT is that  $\partial NF/\partial \alpha < 0.5 \partial P/\partial \theta$ , where NF is the model normal force,  $\alpha$  the angle of attack, and  $\theta$  is the sting deflection angle resulting from an applied load, P, at the balance pitch center location.

*Sting bending.* In order to calculate the divergence limits of a sting it may be necessary to measure its bending characteristics. This may be accomplished by hanging static weights on the sting and measuring the deflection of the sting under simulated load. A semi-automatic system is available in the plenum for performing sting deflection calibrations. The system employs a nested stack of weights on the plenum floor in conjunction with a powered actuator to apply selected loads through the slots to the sting-balance combination mounted in the test section.

*Fouling strips.* For situations where sting and balance bending characteristics indicate the possibility of model-to-sting fouling, fouling detection strips may be mounted between the model and sting to signal contact between the two surfaces during testing.

## Model Balances

The general policy for the facility is that investigations be conducted using strain gage force and moment balances provided by the NASA Langley Research Center. Non-NASA balances may be used provided the balance is, or can be made, compatible to the 8-ft TPT data acquisition system and also provided the balance is made available far enough in advance of the intended test date so that a complete combined loads calibration may be made.

In all cases, balance load limits should be sized to provide accurate results based upon loads expected during testing. In addition, final selection of a balance should be made only after

consultation with Langley balance engineers since balances are continually added to and removed from inventory.

## **Shop Facilities**

Limited shop facilities are located on the second and third floors of Building 640 and are adequate for normal model assembly and checkout, minor model modification, limited fabrication of small parts, and model finishing. More complicated modification or fabrication of precision components must be handled through the Langley shop facilities.

## **Data System**

This section is intended as a general description of the 8-ft TPT data acquisition and processing system. It is not an operations manual but is provided in order to familiarize the reader with the capabilities and configuration of the system.

The system includes two 32-bit high-speed computers built by Modular Computer System, Inc. and referred to as "MODCOMP" computers. The software was developed from modifications to existing software at the 16-ft Transonic Tunnel in 1989 following the laminar-flow-control experiment and supports both 2-D and 3-D testing. It currently includes 128 analog data channels, 16 digital data channels, and 1024 ESP channels (2 ESP DACUs).

A patchboard system is used to bring the input analog signals into the MODCOMP. The output signals from various instruments can be plugged into junction boxes located near the tunnel test section or in the shop area outside the tunnel (for pre- and post-test model instrumentation check out). The analog junction boxes and a thermocouple reference box all feed into an analog sub-patch board in the plenum which permits the desired channels from the various junction boxes to be selected and routed to the main analog patch board in the control room where the signals are assigned to specific channels. The analog sub-patch is also used to route dc power to the strain gage balances. Channel or facility changes may be made easily and rapidly using the patch board systems.

In addition, there are 46 locations or fields of data which are allocated for input digital constants. The first 10 are hard coded for test, run, and point numbers. These input constants are entered into the MODCOMP through ISC touchscreens.

## **Pressure Instrumentation**

Three types of pressure instrumentation are used in the facility; sonar-sensed mercury manome-

ters, an electronically scanned pressure system, and individual pressure transducers. A mechanical stepping valve system, used earlier, has been abandoned.

Freestream stagnation and plenum static reference pressures are measured on sonar-sensed mercury manometers that have already been discussed.

Model pressures are normally measured using the electronically scanned pressure measurement system or individual pressure transducers. It is recommended that wherever possible pressure instrumentation be mounted within the model in order to reduce pressure settling time and the necessity for routing pressure tubes on the outside of the model and main sting. Tubing used for pressure orifice installations should be sized to provide a reasonable orifice size (generally between 0.020 and 0.30 in. I.D. for model sizes previously noted) and to be compatible with existing ESP and stepping valve tubing (O.D. = 0.040 or 0.0625 in., respectively) in order to avoid the use of tube reducers during hookup.

Installation of instrumentation within the model should consider provision for easy access to facilitate transducer range changes or to provide for easy trouble-shooting when problems are encountered. Transducer sizes should be selected to obtain the best possible accuracy based upon expected model pressures and available reference pressures (usually, tunnel freestream stagnation or plenum static pressure).

### **Electronically Scanned Pressure System**

The electronically scanned pressure (ESP) measurement system (Model 780B) is a fully integrated measurement instrument consisting of modular sensors and a data acquisition microcomputer. It is a self-calibrating system capable of acquiring pressure data at a scan rate of 10 000 measurements/second with a quoted precision of  $[0.0015 \times (\text{Module limit})]/^\circ \text{F}$ .

The system consists of five major components: sensor modules which contain multiple pressure ports, Data Acquisition and Control Units (DACU), interface units which interface the sensor modules to the DACU, a host computer, and a Pressure Calibrate Unit (PCU). The facility MODCOMP computer acts as the host computer and interfaces the user with the DACU. It programs the DACU and directs data flow. In the current configuration the sensor modules and the interface units are located in racks on the floor of the plenum below the test section main support strut. Two DACU's are located in the computer room and each provides control and data acquisition functions for up to 512 pressure channels. The PCU consists of pneumatic valving and high accuracy piezoelectric pressure transducers with quartz sensors. These transducers are manufactured by

Paroscientific Corp. under the trade name Digiquartz. The PCU is physically located in the lower observation room and has three Digiquartz transducers with 30 psi, 15 psi, and 6 psi range. The transducers are physically ordered in a 15, 30, and 6 psi arrangement and must be accessed in that order during a calibration although one or two may be skipped.

The system is a modular system and may be configured in many different ways, both by changes in hardware and software. As currently configured, the system contains two DACU's. Each DACU controls two interface units, each capable of handling sixteen 32-port sensor modules with a potential for 1 024 measuring ports. Normally, each sensor module has only one reference supply pressure for all 32 ports but in order to provide increased accuracy for selected measurements during the LFC Experiment, one interface unit was replaced with what was referred to as an expander box to allow the DACU to "see" six pairs of special 16-port differential pressure modules as six 32-port modules. These special 16-port modules were designed to have individual reference pressures to each port instead of one reference pressure for the whole module and were referred as Delta-P modules. The system is thus configured to have the equivalent of 30 32-port modules.

Module hardware currently available consists of three 15 psi-modules (96 ports) calibrated up to 15 psi on a 15 or 30 psi Digiquartz, seventeen 10-psi modules (544 ports) calibrated up to 10 psi on a 15 or 30 psi Digiquartz, five 5-psi modules (160 ports) calibrated up to 5 psi on a 6 or 15 psi Digiquartz, and six 2.5-psi Delta-P modules (192 ports) calibrated up to 2.5 psi on a 6 psi Digiquartz. omit

The system is constrained by the fact that a given Digiquartz standard can only be set to one calibration range at a time and a software restriction that requires all modules in a given calibration group to be adjacent in the hookup order. Current practice is to allocate 10-, 15-, and 5-psi modules as required by the test in progress to the first 24 module slots in the system for a total of 768 ports ( $24 \times 32 = 768$ ). The system does not care if module slots are left empty. The remaining six module slots are reserved for the special 2.5 psi Delta-P modules where each of the 192 ports ( $6 \times 32 = 192$ ) has its own reference pressure. This gives a total capability for the system of 960 ports.

Note that a given module may be calibrated up to the rated full-scale pressure limit (up to the pressure limit of the Digiquartz calibrator). These limits are imposed in different ways: the module can take up to five times the full-scale pressure rating without physical damage, but no data will be obtained above the rated limit because the voltage output is limited to  $\pm 10$  volts; the Digiquartz calibrator would be severely damaged by an overload of more than 20 percent and so is never set to

see a pressure greater than its rated limit.

As mentioned earlier, the sensor modules and interface units are normally mounted in racks on the plenum floor just below the angle-of-attack arc, approximately 40 ft from where a sting mounted model would be located. Since the limitation on the module cable (cable between the module and the interface unit) length is quoted as 30 ft, the system was modified to accept sensor modules in sting mounted models by mounting an auxiliary interface unit in the base of the support strut capable of supporting eight 32-port modules.

### **Individual Pressure Transducers**

An instrument panel is located on the plenum beneath the test section with plumbing to mount 30 individual statham gauges. The plumbing and labeling is currently arranged to mount eight 10-psi transducers, eight 5-psi transducers, eight 2.5-psi transducers, and six 0.5-psi transducers. This configuration is primarily for convenience and other size transducers or combinations of transducers may be used.

The facility inventory of individual statham gauges currently consists of about 50 statham gauges varying in range from  $\pm 0.5$  psi to  $\pm 10.0$  psi.

### **Temperature Instrumentation**

The current capability is available for measuring up to 48 temperatures using chromel-alumel thermocouples. These temperatures are processed through a 150-channel reference junction box mounted in the plenum under the test section—cabling to the data acquisition system in the control room is only available for 48 of these channels, however. This junction box utilizes an electrically maintained 150° F internal reference temperature and is referred to as a “hot” reference junction box. The junction box then automatically adjusts the temperature measured relative to the 150° reference to 32° F for output to the data acquisition system.

### **Miscellaneous Operating Considerations**

#### **Scheduling**

Test schedules are usually updated on a nominally monthly basis and extend for a six month period. Note, however, that some investigations are planned for a year or more in advance and carried in a general listing of proposed tests which are not firmly scheduled. Testing backlog varies somewhat, but generally averages about 12 to 18 months.

Scheduling is considered to be flexible in the sense that although specific dates for testing are scheduled some variation will usually occur as a result of the progress of earlier scheduled tests and changing priorities. A special effort is made to meet firm dates associated with contractual obligations or evaluations, however.

Testing in the facility is generally restricted to in-house NASA research, tests resulting from inter-agency agreements, and tests in support of NASA contracts. Cooperative tests are conducted with industry when it is in the best interest of the NASA to do so.

### **Run Considerations**

Earlier a "run" was conventionally defined as an angle-of-attack sweep at a fixed Mach number for a given configuration. This definition was somewhat arbitrary, however, and any convenient set of test conditions could be grouped as a "run". Typically, several runs comprised the investigation of a single configuration and, based on experience, required two or three hours of tunnel operational time for testing at atmospheric pressure. The conduct of investigations at high or low stagnation pressures or conducting tests at constant Reynolds numbers results in increased operating time because of the pumping time involved.

Because of new data acquisition and data reduction software adopted in 1989, a run was redefined as the total set of operating conditions from tunnel startup to tunnel shut down regardless of operating sequence. Point numbers advance continuously through an entire test without being recycled.

### **Power Considerations**

Electrical power at the Center is shared among the various facilities. As a result, power delays are experienced from time to time, particularly during the summer months, whereby the facility is unable to run or is run only on a limited power basis. These delays are impossible to predict with any certainty but generally occur from early July to mid-September. Because of the resulting competition for power among the larger wind tunnels limits are sometimes imposed on the time the tunnel may be allowed to reserve power between successive runs.

The design of models should therefore include provision for rapid configurational changes. The goal is to provide for a model configuration change within a 20 to 30 minute time period (including model finishing). With such capability, model work may often be performed without loss of power and a greater number of model configurations can be investigated for a given tunnel occupancy

period.

Another advantage of rapid model configuration changes is that they may permit the tunnel to be brought down on what is referred to as a "partial stop". This allows the auxilliary mechanical equipment and main drive electrical equipment to remain on and to idle for short periods of time after the fan has been brought to rest without losing power or having to wait for equipment to coast down before restarting. Such partial stops result in a considerable increase in operating efficiency since several model configurations can be investigated before it is necessary to bring the facility off-line for maintenance checks. They are generally limited by equipment overheat and restricted to about 30 minutes.

If the partial stop time limit is exceeded, or if overheating occurs, and the electrical equipment is then brought off line, it takes about an additonal 30 minutes for the equipment to coast down to where it can be restarted. If the time required for a model change is marginal and if power retention is not a problem it may be wiser to not attempt a partial stop but to go ahead and turn all equipment off so that by the time the model change is completed the equipment has coasted down and is ready to restart.

### Facility Flooding

As may be seen from the photographs in figures 1 through 9, the complex is near sea level and subject to tidal flooding several times a year. The most severe flooding since the construction of the 8-ft TPT occurred in March of 1962 when water levels reached more than 8 ft above mean sea level—almost to the floor level of building 641. This flooding is referred to as the Ash <sup>W</sup>Wednesday Flood and figure 26 shows several snapshots taken around the facility at this time. Although difficult to see, the snapshot in the top left corner of figure 26 shows that waves crashing into the corner of the center section and southern wing of building 641 reached the second story window level.

Langley emergency procedures require that certain precautions be taken to protect tunnel equipment when water levels are predicted to be above certain critical levels. The lowest floor level of the office building facing the water (building 641) is 8.84 ft above mean sea level, but there are condensate pumps in pits under the main drive electrical motors for which the critical water level is only 6 ft above mean sea level. The lowest floor elevation of building 640 which houses much of the auxiliary equipment associated with the tunnel is 7.05 ft above mean sea level but since the electrical equipment is on concrete pads, the lowest critical water lever is 8 ft above mean sea level. There are several cooling water pumps in building 640 that are in pits whose floor levels are lower

than the 8 ft critical level but they are surrounded by a retaining wall whose height is 10 ft above mean sea level.

### Winterization

Until 1984, certain safety precautions were required to prevent freeze damage to the facility whenever the overnight, holiday, or weekend temperatures were expected to go below a certain critical temperature. In December of 1983, there was considerable freeze damage to several pieces of major equipment when a long, unexpected period of very cold weather occurred over a holiday weekend. Since that time, standard operating procedures to prevent freeze damage have required that the winterization procedures be performed any time the facility is left unattended between the first of November and the end of March.

In addition to the winterization procedures, certain pieces of critical equipment and the cooling tower are monitored by freeze alarms which emit audible alarms in the facility and in the fire station.

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