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NASA Glenn 1– by 1–Foot Supersonic Wind Tunnel User Manual

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Summary

This manual describes the NASA Glenn Research Center's 1- by 1-Foot Supersonic Wind Tunnel and provides information for customers who wish to conduct experiments in this facility. Tunnel performance envelopes of total pressure, total temperature, and dynamic pressure as a function of test section Mach number are presented. For each Mach number, maps are presented of Reynolds number per foot as a function of the total air temperature at the test section inlet for constant total air pressure at the inlet. General support systems—such as the service air, combustion air, altitude exhaust system, auxiliary bleed system, model hydraulic system, schlieren system, model pressure-sensitive paint, and laser sheet system—are discussed. In addition, instrumentation and data processing acquisition systems are described, pretest meeting formats and schedules are outlined, and customer responsibilities and personnel safety are addressed.

1.0 Introduction

The 1- by 1-Foot Supersonic Wind Tunnel (1×1 SWT), located at the NASA Glenn Research Center at Lewis Field (adjacent to the Cleveland Hopkins International Airport in Cleveland, Ohio, fig. 1) is available for use by qualified researchers. This manual describes the facility and details procedures for its use. The facility is managed and operated by the Facilities and Test Engineering Division (FTED).

The 1×1 SWT can operate at discrete supersonic Mach numbers from 1.3 to 6.0 in the tunnel test section. The tunnel test section is 53.25 in. long. The cross section of the entrance, which is normally 12-in. high by 12.2-in. wide, can be adjusted to 12-in. high by 14.2-in. wide (horizontal expansion) or to 14-in. high by 12.2-in. wide (vertical expansion). References 1 to 9 present research activities that have been conducted in the facility. These activities include inlet development, computational fluid dynamics validation, basic flow physics investigations, and the development of experimental techniques.

A symbols list for all parameters is presented in appendix A. To schedule tests or inquire about the operation of the 1×1 SWT, contact the facility manager (see app. B).

2.0 Description of the 1- by 1-Foot Supersonic Wind Tunnel

2.1 General Description

Glenn's 1×1 SWT (fig. 2) is a continuous flow facility that can achieve discrete test section Mach numbers of 1.3, 1.6, 2.0, 2.5, 2.8, 3.0, 3.5, 4.0, 5.0, 5.5, and 6.0. For each discrete Mach number, a different nozzle block (fig. 2) is installed in the tunnel test section. Each nozzle block is designed to withstand a pressure of 150 psig. In addition, nozzle blocks for Mach 2.8, 5.0, 5.5, and 6.0 have been hydrostatically tested to 225 psig.

2.2 Tunnel Test Section Envelopes

Centrifugal compressors located at remote sites deliver a desired total air pressure level to the facility entrance (40 or 150 psig). These pressures can be varied by adjusting the facility's valves before the air enters the surge tank (see fig. 2). Figure 3(a) presents the ranges of possible total pressures (as observed and documented during 1 × 1 SWT operation) as a function of the test section Mach number.

The total temperature of the air in the facility test section can be controlled with a facility air heater (see fig. 2 and section 2.3.1). Figure 3(b) presents the variation of total temperature as a function of test section Mach number. From Mach 4.0 to 5.0, this figure shows a drop of 100 °R in the total air temperature in the test section. The highest temperatures at a given Mach number occur at the lowest total pressure, which generates the lowest flow rate through the nozzle block. The Mach 5.0 nozzle block requires a starting total pressure of 65 psia in comparison to the Mach 4.0 block, which requires a starting total pressure of 11.5 psia. With the heater operating at maximum power for both the Mach 4.0 and 5.0 blocks, the minimum flow rate for Mach 4.0 is 2.51 lb_m/sec and that for Mach 5.0 is 6.37 lb_m/sec. The difference in rates results in the lower maximum temperature at Mach 5.0.

Figure 3(c) shows the dynamic pressure as a function of the test section Mach number. As shown, the dynamic pressure decreases starting at Mach 3.5. This is due to the rapid decrease in static pressure.

Figure 3(d) presents the Reynolds number per foot as a function of the test section Mach number. Appendix C gives the Reynolds number per unit length equation, and table I presents the range of values for the facility discrete Mach numbers. From figure 3(d), we see that the maximum Reynolds number per unit length at Mach 4.0, 5.0, 5.5, and 6.0 continues to decrease. This results from the total pressure being fixed at 165 psia because of a facility limit; the total temperature, however, continues to increase with increasing Mach number.

A series of maps in figures 4(a) to (k) present the variation of the Reynolds number per unit length as a function of the test section total temperature for a fixed test section total pressure. These maps can help customers select conditions for tentative runs at the facility.

TABLE I.—MAXIMUM AND MINIMUM REYNOLDS NUMBERS PER UNIT LENGTH AT EACH MACH NUMBER SETTING

Mach number	Minimum Reynolds number per unit length, *Re/L*	Maximum Reynolds number per unit length, *Re/L*
1.3	1 819 000	10 069 000
1.6	1 649 000	11 172 000
2.0	1 329 000	13 031 000
2.5	1 062 000	16 040 000
2.8	889 000	18 243 000
3.0	786 000	19 893 000
3.5	520 000	20 299 000
4.0	361 000	15 940 000
5.0	1 430 000	8 141 000
5.5	1 375 000	5 850 000
6.0	1 555 000	4 282 000

2.3 Description of Major Tunnel Components

The major components of the 1 × 1 SWT are illustrated in figure 2.

2.3.1 Air heater.—The 665-kw air heater can supply constant-temperature air to the facility test section. It is located in the mezzanine area of the facility (see fig. 2).

2.3.2 Air inlet line and surge tank.—The air inlet line to the surge tank (see fig. 2) provides the tunnel with 40- or 150-psig dry air at an approximate dew point temperature of –20 °F. The air flows into the 6-ft-diameter surge tank, where it passes through a honeycomb and screen arrangement inside the tank prior to entering the nozzle section of the tunnel (see fig. 2). This improves the flow quality of the air.

2.3.3 Nozzle section.—After the air exits the surge tank, it enters an interchangeable 88-in.-long nozzle block (see figs. 2 and 5). Each nozzle block is two-dimensional, with flat ceilings and floors, and sidewalls contoured to produce a discrete supersonic Mach number—1.3, 1.6, 2.0, 2.5, 2.8, 3.0, 3.5, 4.0, 5.0, 5.5, or 6.0. These interchangeable blocks, which are stored in the mezzanine area of the facility (see fig. 2), have entrances and exits that are 12-in. high by 12.2-in. wide.

A hydraulic lift support beneath the test section (see fig. 2) must be used when a nozzle block is removed or installed. The lift vertically lowers the existing nozzle block from the test section area to the mezzanine of the facility; then technicians manually replace it with a block that will produce the desired test section Mach number. This interchange takes about 10 minutes. For Mach 1.3 to 4.0 only, the aft 15.5 in. of the nozzle blocks is not contoured. As a result, with these blocks models can extend forward of the test section inlet without affecting the incoming Mach number.

There is one 12-in.-diameter port for customer use located at the bottom of the aft section of each nozzle block. The vertical centerline of this port is 15.5-in. upstream of the entrance to the existing facility test section (see the elevation view in fig. 5). The port in the nozzle section floor is removable; it can be replaced with stainless steel, aluminum, or Plexiglas and can be modified as needed. This port can be used to fasten a model to the aft section of a nozzle block. Note that when a change in test section Mach number is desired, any model mounted to this port must be disconnected before the nozzle block can be interchanged safely.

2.3.4 Test section.—The inside of the test section is 12-in. high, 12.2-in. wide, and 53.25-in. long (see fig. 6(a)). It can be expanded to 12-in. high by 14.2-in. wide. This horizontally expanded wall configuration (see fig. 6(b)) may be useful for certain tests or for tunnel startups under certain circumstances. The test section also can be expanded to 14.0-in. high by 12.2-in. wide. This vertically expanded wall configuration (see fig. 6(c)) is required for certain tests.

A window can be installed in any of eight positions in the test section (four forward and four aft). Multiple windows can be installed in the test section at one time, except on adjacent forward or aft sides. They can be installed upstream and downstream of each other on the same side. Blanks can be installed in the remaining openings. Figures 6(a) to (c) show schematics of these configurations. The viewing area of each glass or schlieren-quality glass window in the test section is 11.8-in. high by 22.35-in. long, an area of 263.73 in.^{2} Figure 7(a) is a photograph of an elevation view of the test section installed in the tunnel, as seen from the west side of the facility. Figure 7(b) is a photograph of an isometric view of the test section from the west side of the tunnel.

Another option for the 1×1 SWT test section is the false floor setup. This configuration can be used to install an instrumented plate or other model or support hardware. Figures 6(b) and (c) show the opposing flow surfaces of the test section for a false floor configuration. Any one of the four internal flow surfaces can be independently configured for the false floor. Each changes the test section cross section by 1 in. The FTED project engineer and the facility lead mechanic can be contacted to discuss its use.

2.3.5 Transition section.—The transition section is shown in figure 6(a). It begins at the exit of the tunnel test section as a 14.21-in.-high, 12.2-in.-wide rectangle, and it terminates as a circular section with an inner diameter of 15.125-in. The total length of this section is 5.62 in.

2.3.6 Diffuser section.—The diffuser section connects the transition section with the altitude exhaust system (see fig. 2).

2.4 Control Room

The control room used to operate the 1×1 SWT is located on the first floor adjacent to the test cell. Tunnel and model operators use the control panels located in the middle of this room (see fig. 8). Research engineers and model operators use the control panel and computer equipment located in the foreground of the room. An interactive color graphics control system, referred to as the "Programmable Logic Control (PLC) system" is used to set tunnel conditions and is located at the tunnel operator's panel. Model or test article controls are located on a separate interactive color graphics panel. Test section models can be remotely viewed on monitors in the control room.

The control room also contains Glenn's data-acquisition system, Escort D, and the electronically scanned pressure system (ESP) available for model instrumentation. The Escort D system is interactive (push button), and it can collect, process, display, and record data as results accumulate during a test. See sections 5.1 and 5.2 for details on the electronically scanned pressure system and the Escort D systems.

The control room can be completely secured for sensitive test programs. Security should be discussed with the 1×1 SWT facility manager and the FTED project engineer during one of the pretest meetings at Glenn.

3.0 General Support System

3.1 Air Pressure Systems

Table II presents pertinent information on facility support systems.

3.1.1 Service air.—Service air with a capacity of 2.0 lb$_m$/sec is available at 125 psig.

3.1.2 Combustion air.—The central combustion air system can provide 40, 150, or 450 psig air to the facility. For 40- and 150-psig air, the standard flow rate that can be delivered to the facility is 60 lb$_m$/sec; and for 450-psig air, it is 2 lb$_m$/sec. It is possible to attain a flow rate of 100 lb$_m$/sec with restricted availability. If required, this high flow rate should be discussed with the FTED project engineer and the facility lead mechanic. Combustion air is provided to the facility surge tank at 40 or 150 psig (see fig. 2). The 450-psig combustion air is provided to the facility test section and/or bleed line ejectors through a 3-in.-diameter stainless steel line to accommodate model supply pressure applications. Facility valves can be used to vary this pressure from 20 to 450 psig.

TABLE II.—FACILITY SUPPORT SYSTEMS

System	Weight or volumetric flow rate	Pressure	Temperature
Service air	2 lb$_m$/sec	125 psig	----------
Combustion air	[a]60 lb$_m$/sec	40 psig	[d]Ambient to 650 °F
Combustion air	[a]60 lb$_m$/sec	150 psig	[d]Ambient to 650 °F
Combustion air	2 lb$_m$/sec	450 psig	[d]Ambient to 650 °F
Nitrogen	0.2 lb$_m$/sec	2200 psig	Ambient
Ethylene gas	6.0 std liter/min	2 to 3 psig	Ambient
Altitude exhaust	[b]60 to 100 lb$_m$/sec	4.0- to 28-in. Hg	Ambient
Auxiliary bleed	0 to 3.5 lb$_m$/sec	[c]0.3 psig	Ambient
Hydraulic	3 gpm	1500 psig	----------

[a] Higher flow rates can be provided, but this requires additional scheduling coordination.

[b] The standard altitude exhaust flow rate is 60 lb$_m$/sec. Under certain circumstances, an altitude exhaust flow rate to 100 lb$_m$/sec is possible.

[c] Contact facility personnel for specifics.

[d] The temperature of the combustion air depends on the required mass flow rate. Temperature variation is from ambient to 650 °F, with temperatures above 250 to 300 °F restricted to Mach 5.0 and above.

3.2 Nitrogen Gas System

Gaseous nitrogen, which is located in a tank adjacent to the facility, is used for pressure control, valve actuation, and purging. The pressure inside the tank is 2200 psig, and nitrogen is normally delivered to the facility at 2000 psig. However, this pressure can be regulated from 100 to 2000 psig to meet customers' needs. The maximum nitrogen flow from the storage tank to the facility test section is 0.2 lbm/sec.

3.3 Ethylene Gas System

The 1 × 1 SWT trace gas system quantitatively measures the mixing characteristics of research hardware and the mass flow rate of specific flow fields. The system uses ethylene (C_2H_4) as the trace gas.

For measurements of the mixing characteristics of research hardware, a metered flow of ethylene is injected and allowed to diffuse into the desired flow field. Downstream of the injection point, a pitot probe samples the desired flow field at discrete points in the survey plane. At each discrete point, the pitot probe sample is delivered to a hydrocarbon analyzer that burns the sample and determines its hydrocarbon content. After the survey plane is sampled, lines of common hydrocarbon content are plotted in parts per million (ppm). This plot provides a quantitative measurement of the flow field mixing characteristics.

Another use for the ethylene trace gas system is measuring the absolute mass flow of the facility's auxiliary bleed system. For these measurements, the bypass flow is seeded with ethylene gas at a known mass flow rate. At a survey plane downstream (far enough downstream to provide thorough mixing of the ethylene and the auxiliary bleed system flow), a sample of the mixed flow is collected and delivered to the hydrocarbon analyzer. This analyzer then returns the measured volume fraction of ethylene contained in the sample. In this sample of ethylene and air, the mass fraction of ethylene is defined in terms of the volume fractions of the two components (ethylene and air). Combining these two relationships results in a singular solution for (1) the mass flow rate of the bypass air as a function of the volume fraction of ethylene, (2) the molecular weights of air and ethylene, and (3) the ethylene injection rate. A thorough discussion of the operating principles and applications of this ethylene trace gas system are provided in reference 10.

3.4 Altitude Exhaust System

Altitude exhaust can be provided to the facility test section exit through the 48-in.-diameter line shown in figure 2. The maximum vacuum pressure that can be provided to the test section is 28 in. of Hg, and the maximum flow rate available with this vacuum pressure is 60 lb_m/sec. Other vacuum pressures to approximately 4 in. of Hg are available. Customers can consult with the FTED project engineer to request desired vacuum pressures and flow rates.

3.5 Auxiliary Bleed System

Two lines are available for bleed studies (see fig. 2); both are connected to the central altitude exhaust system. One is 16 in. in diameter and has a minimum line pressure of 28 in. of Hg vacuum. The other is 10 in. in diameter and has a minimum line pressure of 29.4 in. of Hg vacuum. This second line also has two ejectors upstream of the final connection into the central altitude exhaust line.

A bleed housing exhaust plenum (see fig. 9) is used for sidewall bleed studies. It is mounted on the same side of the tunnel as the bleed pipes (see fig. 2).

A series of bleed plates support testing in the 1×1 SWT. These plates have a flow surface size of 6 in. (streamwise) by 7 in., with a variety of bleed patterns. Figures 10(a) to (d) show four examples of the current plate selection in the 1×1 SWT.

Bleed plates are typically installed flush to the internal flow surface within a test section wall. The backside of the bleed plate is connected to the 1×1 SWT bleed exhaust plenum, which is connected to the piping system that provides a variable vacuum source. The pressure differential created by the higher flow surface pressure versus the lower vacuum system pressure allows the internal tunnel flow to be bled first into the exhaust plenum and then into the bleed piping system. Typically, these plates are used to control boundary layer height and shock-boundary layer interactions. Customers should consult with the FTED project engineer if they require additional details related to the current set of available bleed plates and their flow capabilities.

3.6 Model Hydraulic System

A hydraulic actuation system that uses four Moog servovalves is available for customer use. These valves, which are mounted approximately 3 feet above the transition section of the facility, are attached to flexible stainless steel tubing that routes the hydraulic fluid to the required model actuation system. The hydraulic system pressure is usually 1500 psia with a system flow rate of 4 gpm.

3.7 Schlieren System

1×1 SWT customers can use our schlieren system, which is mounted on a 20.5-in.-wide, 67-in.-long portable stand. When in use, this system is positioned at the facility test section so that it can view an 11-in.-diameter image anywhere within the 11.8-in.-high, 22.35-in.-long window (see fig. 6(a)). This system is usually configured for operation in the vertical plane, but it can also be configured for the horizontal plane to accommodate a model-mounting configuration. Schlieren-quality glass windows are installed in the test section when the schlieren system is being used.

Schlieren images are viewed with a video camera and a control room monitor. A video cassette recorder is used to record these images on tape so that they can be analyzed later. In addition, schlieren images can be photographed with a Nikon 35-mm camera. Up to 36 photographs can be taken without reloading. If required, a high-speed camera can be installed in place of the 35-mm camera. This equipment can be rented from the Imaging Technology Center.

Figure 11 shows a schlieren photograph of an isolated boundary layer simulator model at Mach 4.0. The characteristics of the exiting flow can be seen downstream of the boundary layer simulator, and two families of waves can be observed. Figure 12 shows schlieren results at Mach 2.5 for a shock generator plate inclined 8° relative to the incoming airflow. The flow proceeds from left to right, and a compression fan/reflected shock system can be seen. In addition, there is evidence of an expansion fan in the reflected shock wave. Schlieren work that has been done at the facility is discussed in detail in references 4 and 9.

3.8 Model Pressure-Sensitive Paint

3.8.1 Paint background.—Pressure-sensitive paint can be applied to a model surface as a flow-visualization technique to produce a global pressure map of a model. For this technique, all surface oils and dirt must first be removed by cleaning the model surface with isopropyl alcohol. Any unwanted surface imperfections must be corrected before a final cleaning of the model surface with a solvent. Next, primer paint is applied. The primer serves two purposes. First, it enhances the bonding between the pressure-sensitive paint and the model surface. Second, because it is white, it increases the amount of light that can be picked up by the detection system. MDA PF2B paint, the pressure-sensitive paint used at Glenn, was developed by McDonnell-Douglas. Reference 11 includes a thorough discussion of the use of this flow-visualization technique at Glenn.

3.8.2 Pressure-sensitive-paint data acquisition system.—The pressure-sensitive-paint portable data acquisition system consists of a personal computer, tungsten halogen lamps, a camera, and an imager. The personal computer stores the images and handles all data reduction routines that are required to produce quantitative global pressure measurements. It can be connected to an Ethernet network for downloading information from other computers for further data analysis. The camera communicates to the personal computer through a controller board. The controller handles all camera control functions and data transfer. Image data must be transferred immediately to the PC's memory because the camera has no memory to store data.

Several standard tungsten halogen lamps are used to excite the paint molecules. These 75-W, 12-V lamps have the type of integral reflectors that are commonly used for display lighting. Three different reflectors are available, giving a beamspread of 14°, 25°, or 42°. A combination of lights and lenses can be used to project light with a 12-in.-diameter beam, up to a distance of 25 ft.

The final component of the system is an imager. The imager is usually made of silicon, which has favorable properties when exposed to electromagnetic radiation in the visible spectrum. The electric charge generated in the imager is proportional to the light in the visible wavelength band that is incident on the imager. This charge is stored in the imager so that it can be measured. Reference 11 gives a detailed description of the halogen lamps, imager, and personal computer that are used in Glenn's pressure-sensitive-paint data acquisition system.

3.9 Oil Flow-Visualization System

Two oil flow techniques have been used at the 1×1 SWT. The first uses a blue Zyglo and oil mixture illuminated by ultraviolet light. A blue Zyglo and oil mixture is painted on a model; then, the tunnel test section is closed and the facility is run at test conditions for approximately 10 min. Next, the tunnel is shut down and reopened, and photographs of the Zyglo-oil pattern deposited on the model are taken using ultraviolet lights. This technique appears to work best with stainless steel or aluminum models, but it has yielded satisfactory results on black oxide carbon steel models. Oil flow visualization can also be used on internal surfaces if the model can be disassembled in 10 min or less so that gravity effects do not distort the streamlines. Surface oil flow visualization was used to investigate near-wall flow behavior for a hypermixing nozzle study (ref. 12) and tunnel flow interaction resulting from a single flush-mounted, hypermixing nozzle (ref. 13). The second oil flow technique used at the 1×1 SWT mixes fluorescent powders with oil and follows the same procedures as for the first technique.

Figures 13 and 14 show photographs from typical oil flow-visualization studies performed at the 1×1 SWT on the Mach 5 inlet model. Figure 13 shows plan view results for a model tested at Mach 2.5 and positioned inline with the flow direction (which is from left to right in the figure). Figure 14 shows elevation view results when the model was tested at Mach 3.5 and inclined downward 8.55° to the flow direction (which also is from left to right in the figure).

3.10 Laser Sheet Flow-Visualization System

A 6-W argon-ion laser coupled with a fiber-optic system, which delivers the laser beam to the test section, produces laser sheets in the 489- and 514-nm wavelength range for the 1×1 SWT. The optic head that houses the lenses is coupled to the fiber-optic cable at the test section end. These lenses can be changed to vary the dimensions of the laser sheet. In addition, the optic package is mounted on a traversing mechanism so that detailed observations can be made over the test section panel insert window. The laser sheets can be setup in different orientations.

Video and still cameras can be used to view the flow field. Color video cameras can be mounted at different test section locations to obtain the best views of the flow field and to obtain maximum light levels. Setups can be discussed with the FTED project engineer and the facility electrical engineer at one of the pretest meetings. Still photographs can be taken with 35-mm cameras. Because the laser system is a shared resource, customers should notify the facility manager at least 6 months before they will need this equipment.

3.11 Photographic Equipment

Photographic and television coverage of tests in the 1×1 SWT can be obtained at the test section window assemblies. Video and still cameras may be used along the test section windows. Customers can use 1×1 SWT equipment: a Nikon 35-mm camera with a standard 60-mm lens or a 60- to 300-mm zoom lens, or a Panasonic video channel recorder (VCR). The VCR uses regular VHS or S-VHS formats and standard play (SP) or standard long play (SLP) tape speeds. Motion picture and digital video high-speed photography are also available. The motion picture cameras operate from 24 to 10 000 frames/sec. The digital high-speed video system (which can be rented from the Imaging Technology Center) produces black and white images with frame speeds adjustable from 1000 (full frame height) to 12 000 frames/sec (variable frame height). The Imaging Technology Center will handle all aspects of imaging required. The 1×1 SWT project engineer will arrange any meetings between customers and Imaging Technology Center personnel.

3.12 Electrical Power System

The following types of electrical power are available at the facility test section:

(1) 440-V, 60-Hz, three-phase, ac power
(2) 208-V, 60-Hz, three-phase, ac power
(3) 120-V, 60-Hz, one-phase, ac power

3.13 Electrical Cabling System

Electrical cables from the model are terminated in connectors that are approximately 15 feet from the test section. These connectors mate with an existing cable system that extends into the facility control room. Descriptions of the types of cables that are available follow:

Type B cables are used for strain gauges and special pressure transducers. Type D cables are used with potentiometers. Each customer device should use an individual cable. Differential transducers should use separate power and signal cables. The types and numbers of cables available as well as termination details are given in table III.

TABLE III.—CABLING DETAILS

Type	Quantity	Cable	Cable terminal connector to the control room	Required mating connector
B	16	6 conductor no. 20 AWG shielded[a]	MS–3106–14S–6S	MS–3106–14S–6P
D	16	3 conductor no. 20 AWG shielded[a]	MS–3100–143–1S	MS–3100–14S–1P

[a] AWG, American Wire Gauge.

3.14 Probe Actuator Control System

The Probe Actuator Control System (PACS) can simultaneously control up to eight dc stepping motors of up to 1600 oz-in. torque. It can also integrate the automation of survey patterns with the Escort D data acquisition system. Customers can discuss the system's capabilities with the FTED project engineer and the facility electrical engineer at one of the pretest meetings.

3.15 Model Preparation Area

The model preparation room (see fig. 15), which is adjacent to the facility control room, is available to customers during model assembly. Because this room is used for other purposes, 1×1 SWT users may have to share the area with people working on different programs.

3.16 Shop Equipment

The 1×1 SWT shop contains numerous machine tools: a drill press, an engine lathe, a milling machine, a vertical saw, a surface grinder, a cut-off wheel machine, a band saw, a tig welding machine, and a shielded metal-arc welding machine. Customer use of this equipment must be cleared with the FTED project engineer and the facility lead mechanic.

4.0 Instrumentation

Model and tunnel instrumentation can include any combination of pressure modules, individual pressure transducers, thermocouples, attitude indicators, strain gauges, and potentiometers. Measurements by this instrumentation can be monitored and recorded by the facility data acquisition system (ESCORT D see section 5.1) or by a customer-supplied data acquisition system.

The output of facility instrumentation used to operate the tunnel is normally displayed on the Programmable Logic Control system graphics. The Programmable Logic Control system is a computer with specialized software used by the tunnel operator to control the tunnel. It is used for alarm monitoring and reporting tasks, and acts as an interlock for controlling facility valves.

4.1 Thermocouples

All model thermocouples should be made with high-temperature, glass-insulated thermocouple wire appropriate for maximum test conditions. Leads extending from the model should be at least 15 feet long and should terminate in Marlin Manufacturing Company standard two-pole male ends or the equivalent. All model thermocouple wires must terminate in terminal panels that are located near the facility test section. There are 48 channels available for temperature measurement. The FTED project engineer and the facility electrical engineer can provide customers with detailed information on the length of the thermocouple leads at one of the pretest meetings. Thermocouples should be either Type E or K. Table IV lists the male and female connector model numbers for these thermocouples.

Thermocouple alloy wires extend from the terminal panels to thermocouple junction reference units in the control room. These reference units are held at 150±0.25 °F. Copper cables are run from the reference unit to the control room patchboard. All thermocouples can be patched into the Escort D data-recording system (see section 5.1).

TABLE IV.—THERMOCOUPLE INFORMATION

Thermocouple type	Wire type	Male (plug) Marlin model	Female (jack) Marlin model
E	Chromel/constantan	1060–E	1010–E
K	Chromel/alumel	1060–K	1010–K

4.2 Actuators and Position Indicators

Screwjacks and hydraulic cylinders are commonly used to remotely position wind tunnel models and their components. Electrically driven screwjacks should be provided by customers, with limit switches to protect the model, its components, and the mechanism from damage caused by overtravel. Hydraulic cylinders should be sized so that their travel cannot exceed safe limits, and they should be cushioned if they are to move rapidly. The hydraulic system capacity is noted in section 3.6. Linear voltage differential transducers (LVDT's) provide remote position indication. All actuators and position transducers must be able to withstand tunnel test section operating conditions.

5.0 Data Acquisition and Processing

5.1 Electronically Scanned Pressure System

The facility's electronically scanned pressure system provides high-accuracy measurement of steady-state model and facility pressures at a high acquisition rate. The system uses plug-in modules, each containing 32 individual transducers that are addressed and scanned at a rate of 10 000 ports/sec. Up to 18 modules with 31 ports per module may be used, providing a maximum of 558 pressure channels. The transducer ranges are from ±5 to ±500 psid. Table V describes the number of modules available for each transducer range and the number of pressure channels available at each transducer range. Reference and check pressures are obtained from remotely controlled regulators.

Normally, all transducers are calibrated online every 60 min by the operation of a pneumatic valve in each module which switches the system into a calibrate mode. Three calibration pressures, measured with precision digital quartz transducers, are applied in up to five ranges to assure that overall system errors are not greater than ±0.07 percent of full scale.

TABLE V.—TRANSDUCER MODULE INFORMATION
[Port size, 32.]

Transducer	Transducer range, psid	Transducer accuracy, psia	Number of modules	Number of channels available
1	±5	±0.0035	(a)	(a)
2	±15	±0.0105	(a)	(a)
3	±30	±0.0210	(a)	(a)
4	±100	±0.0700	(a)	31
5	±250[b]	±0.1750	1	31
6	±500[b]	±0.350	1	31

[a] The number of modules and channels available can vary. This feature should be discussed with the facility electrical engineer.

[b] It is only possible to use one of these modules at a given time.

5.2 Escort D

Glenn's Escort D system (see ref. 14), which is supported by Glenn's Computer Services Division, is a minicomputer-based, real-time data-acquisition, display, and recording system that is generally applicable to steady-state tests. Analog data from the experiments are digitized and then acquired by a Digital Equipment Corporation (DEC) Alpha computer located in the 1×1 SWT control room. Recorded data are transmitted through a network link (for unclassified projects) to a central mass storage system in the Research Analysis Center (RAC) for later batch processing if necessary. Data from sensitive projects are stored on removable disks associated with the DEC Alpha computer system. Sensitive data are reprocessed in batches on the DEC Alpha system as runs are completed. In addition, sensitive data can be transferred to 4-mm tape or to a local PC for later processing on other secured computer systems. Real-time processing tasks include acquiring data, converting raw counts to engineering units, performing online calculations, updating facility display devices (both alphanumeric and graphical), and transmitting data for archival recording on a data collector. The update time for a standard program is 1 sec.

Figure 16 shows the flow of information between the facility computer and the Research Analysis Center computers, and figure 17 gives a detailed block diagram of the facility computer. Data can be acquired and processed by using standard data software programs along with software specifically designed and programmed for the particular test. Program availability can be discussed at one of the pretest meetings.

5.2.1 Real-time displays.—Customized Escort D output programs can be developed to display all data channels and computations selected for a given test program in an alphanumeric format. This output can be displayed on a variety of control-room CRT's (cathode ray tubes). Customers can request the type of output that is desired from the facility electrical engineer. The two alphanumeric color CRT's, the one graphics terminal, and the one x-terminal that can be supported on the system provide a means of monitoring the progress of a test and displaying data sets. One alphanumeric CRT is dedicated to the tunnel operator and one alphanumeric, one graphics, and one x-terminal are available to customers. The x-terminal can interface with the Escort D system and can also bring up display pages. Each CRT can view any display page at any time. A laser line printer is available for printing hard copies of the data displayed on the CRT.

Online plots can be defined through a graphics specification language. The Escort programmer does the initial graphics specification, but changes can be made at the facility through an interactive editor. Plot pages and alphanumeric pages displayed on the CRT's are changed by entering their page numbers on a number entry panel.

One individual data display (IDD) can highlight specific test parameters that are defined by users during runs. The display is individually addressable and has one 40-alphanumeric character line. Cursor addressing allows data labels to be fixed and the data to be updated every second.

Special function buttons on each CRT allow users to control display functions, such as creating subsets of test parameters, displaying data in different units (i.e., engineering units, millivolts, or counts), and printing the data displayed on the CRT. At least 8 weeks prior to the start of a program, customers should submit to review any requests for customized output and computed results.

5.2.2 Data collection.—When a customized data software program is installed on the Escort D system and the data record button is activated, all data channels are scanned once, saved locally on Glenn's mass storage system, and assigned a unique reading number. In addition, users can save the average of N (maximum of 20) data scans as a single reading. Data can be processed in real time when requests include the calculation of ratios and of engineering and model performance parameters. Acquired data are postprocessed on the facility's computer system to provide spreadsheets and cross-reading/scan analysis output. If multiple or continuous high-speed scan cycles are needed to define a test condition, the data-record button can be activated for automatic, multicyclic scanning per reading. Multicyclic data are normally used for slow, transient tests or moving-probe hardware tests.

5.3 Dynamic Data Acquisition

5.3.1 Facility tape recorder.—Dynamic data can be recorded on the 21-track instrumentation tape recorder that is available in the control room. These data can be converted to digital tape later with the analog frequency-modulated demultiplexer equipment in the Research Analysis Center. This procedure can be discussed with the facility electrical engineer at one of the pretest meetings.

6.0 Pretest Requirements

The 1×1 SWT is scheduled for year-round, continuous testing. Because of existing commitments and the long lead times necessary for special test requirements, it is advisable to contact the facility manager (app. B) to discuss your preliminary requirements as soon as you have identified the need for testing in the 1×1 SWT. Certain research test projects require a 4- to 6-month lead time. Early notification allows the facility manager and other FTED personnel to review the proposed model design and ensure its compatibility with the tunnel test section.

Non-NASA requestors must send a formal request for tunnel use to Glenn's Director of Engineering and Technical Services. The facility manager can explain the formal request letter and request process further. Upon receipt of a formal request for tunnel test time, the Director of Engineering and Technical Services will review the project with the facility manager. If the project is accepted, a test agreement will be prepared and sent to the requestor for signature. This agreement outlines the legal responsibilities of both Glenn and customers during the time that the project is at Glenn (model arrival, test time, and model return). Customers must sign the test agreement and return it to Glenn.

The four types of test agreements follow:

(1) NASA test program
(2) NASA/industry cooperative program (reimbursable or nonreimbursable Space Act agreement)
(3) Other U.S. Government agency programs (reimbursable or nonreimbursable interagency agreement)
(4) Industry proprietary or noncooperative program (reimbursable Space Act agreement)

Customers must prepare a requirements document and make it available to the facility manager and the FTED project engineer at the first pretest meeting held at Glenn. The facility manager will explain what topics should be addressed in this document. For more information, see appendix D, which outlines the procedure for obtaining tunnel test time.

6.1 Pretest Meetings

A series of pretest meetings are held at Glenn to discuss the test plan, the instrumentation, the tunnel hardware, and the data requirements. The number of pretest meetings held at Glenn or at the customer's site is a function of the test's complexity. These meetings are composed of the customer's lead engineer, key customer personnel, the facility manager, appropriate FTED branch chiefs, key FTED personnel, and the FTED project engineer. A customer checklist for these meetings is provided in appendix E.

6.1.1 Test objectives.—Customers should provide a statement indicating the test objectives and goals, and thoroughly explaining any special test procedures. The customer's lead engineer should also provide a prioritized run schedule that is compatible with the available test window.

6.1.2 Instrumentation.—Customers should provide a list of requested instrumentation to the FTED project engineer. Customer-provided instrumentation will be adapted to the 1×1 SWT data system (see sections 4.0 and 5.0).

6.1.3 ***Hardware.***—Customers must provide drawings of the model installation in the facility test section. To assist customers, the FTED project engineer will provide detailed drawings of the nozzle block section, the test section, and the transition section.

6.1.4 ***Data acquisition and reduction.***—Data reduction information consisting of data input, data output, and equation sets in engineering language must be provided if Glenn is to perform the data reduction. Customers should provide this information to the FTED project engineer 8 weeks before the start of testing. The FTED project engineer will contact the appropriate CSD personnel to set up any necessary meetings between customers and CSD computer specialists. These meetings will establish ground rules for writing the computing requirements. Customers must submit these written computing instructions to the CSD computer specialist 8 weeks before the start of testing. Alternatively, customers may bring a self-contained computer system for data processing. If this option will be used, it should be discussed with the FTED project engineer, the facility electrical engineer, and a CSD representative at one of the pretest meetings.

6.2 Deliverables

Customers should provide the following information to the FTED project engineer 8 weeks before the scheduled test:

(1) Test envelope for the model
(2) Loading on the model—Mach number, dynamic pressure, and model attitude
(3) Stress analysis based on the maximum loads that are anticipated on all sections of the model, per criteria in section 7.3.5
(4) Detailed drawings of the cross-sectional area distribution of the model to allow blockage and air load calculations
(5) Drawings that show model installation and model support systems
(6) All calibration information that is to be supplied by customers
(7) A list of all customer-supplied equipment plus block diagrams and wiring schematics

If the customer and Glenn agree that it would be mutually beneficial, the customer may be asked to supply selected model drawings and/or photographs for reproduction in NASA technical papers.

6.3 Model and Equipment Delivery

All models, instrumentation, and support hardware should be sent to Glenn to the attention of the FTED project engineer (the facility manager will supply the name and the address of this engineer). All model parts, model internal instrumentation, and customer support hardware should be assembled before shipment to Glenn to reduce installation delays. Large shipment crates must have skids so that forklifts can handle them. The delivery date of equipment and/or models will vary according to the model's complexity. The customer and the FTED project engineer should agree on an appropriate delivery time. The model crate and any customer equipment should be delivered to dock 37A of building 37 (see fig. 1 for this location).

7.0 Risk Assessment of Wind Tunnel Model and Test Hardware

The following sections discuss permissible model blockage in the tunnel test section, model design criteria pertaining to loads and allowable stresses, and model fabrication and quality assurance requirements.

7.1 Model Size

Figure 18 shows the maximum projected frontal area for the model and any supporting structure in the tunnel. This figure can be used as a general guide for determining acceptable model blockage in the test section. Standard practice in aerodynamic testing is to limit the model frontal area to less than 10 percent of the cross-sectional area of the tunnel test section. Based on this, the 1×1 SWT frontal area limitation would be 14.64 in.^2 (12-in. by 12.2-in. times 0.1). As shown in figure 18, the tunnel can be started with an inlet model with a blockage of 39 in.^2, or 26.6 percent of the available area, for a test section condition of Mach 3.5. For a 30° half-angle cone model, the tunnel has been started with a blockage of 23 in.^2, or 15.7 percent of the available area, for a test section condition of Mach 4.0.

The Mach 1.3 nozzle block is a special case. This block has a throat area that is 93.8 percent ($A/A^* = 1.066$) of the test section cross-sectional area. It limits the allowable cross-sectional area of the model to (ideally) 6.2 percent of the cross-sectional area of the test section, or 9.07 in.^2 If this criteria is not followed, the model station in the test section becomes the minimum area and the nozzle block will not "start" (i.e., operate supersonically). Consequently, the 1.3 nozzle block should only be used for probe calibration.

Data presented in the Mach 4.0 to 6.0 range on figure 18 were computed from theory presented in an unpublished report entitled "Aerodynamic Calculations for a Small Supersonic Wind Tunnel," which was developed by Sverdrup Corporation for Glenn.

7.2 Model Mounting Systems

Figures 19(a) and (b), respectively, present elevation and front views of a typical model strut mounting system. A hydraulic actuator, which is mounted in a sealed container in the back porthole, is used to pitch the model. The mounting struts and the support brackets are presented in figures 20 and 21, respectively. These struts are available for customer use; but for most models, it is advantageous to use struts designed for the model. Similar mounting systems have also been used to mount shock plates in the tunnel, both vertically and horizontally. Models that need to be actuated during a test can be hard-mounted to any of the existing ports.

7.3 Model Design Criteria

Tunnel test models must be designed for the following applicable load and stress conditions.

7.3.1 Supersonic startup loads.—When model loading is being established for supersonic startup and unstart conditions, an additional 10° flow angle should be added to the maximum model angle of attack with respect to the free stream to establish the model design loads. This should be done in both the pitch and yaw directions. The dynamic pressure used should be the maximum tunnel dynamic pressure as presented in figure 3(c). With this criterion, the allowable stresses should not exceed one-half of the yield stress of the model material. All auxiliary parts of the model exposed to the air stream at a nominal 0° angle of attack should be evaluated at a 10° angle of attack for startup and unstart loads. Models unusual in size, shape, or operation may require special analysis. Loads for such models can be discussed with the FTED project engineer.

7.3.2 Supersonic steady-state loads.—When model loading is established for supersonic steady-state conditions, the model's maximum angle of attack should be used to establish its design loads. This should be done in both the pitch and yaw directions. The dynamic pressure used should be the maximum tunnel dynamic pressure (fig. 3(c)). With this criterion, the allowable stress for maximum loading is the smaller of one-fifth of the minimum ultimate stress or one-third of the minimum yield stress of the model material. This corresponds to a safety factor of 5 on ultimate stress and of 3 on yield stress. Models unusual in size, shape, or operation may require special analysis. Maximum loads for such conditions can be discussed with the FTED project engineer.

7.3.3 ***Supersonic, localized unstart loads.***—When side loads on the model are established for supersonic, localized unstart conditions, the pressure difference across the model should be the static pressure rise across a normal shock for a given Mach number (fig. 22). With this criterion, the allowable stress for maximum loading is the smaller of one-fifth of the minimum ultimate stress or one-third of the yield stress of the model material or of the model. This corresponds to a safety factor of 5 on ultimate stress and of 3 on yield stress.

7.3.4 ***Reduction in safety factors.***—The safety factors discussed in sections 7.3.1, 7.3.2, and 7.3.3 can be reduced to 3 on the minimum ultimate stress and to 1.5 on the minimum yield stress of the model material if the customer can accurately predict stresses. These indepth model stress predictions can employ state-of-the-art structural analysis codes that use finite-element or finite-difference techniques.

7.3.5 ***Model stress analysis.***—Customers must submit a model stress report that is part of a model systems report to the FTED project engineer 8 weeks before the start of testing. The FTED project engineer will outline the requirements of the model systems and model stress reports for customers. The stress analysis should include the following factors:

(1) Dynamic factors that may result from flow separation
(2) Thermal stresses on the model
(3) Stress concentration factors
(4) Wind tunnel steady-state lift and drag forces
(5) Startup and unstart loads
(6) Design safety factors for the types of loading discussed in steps (4) and (5)

These calculations should show that the allowable stresses are not exceeded for the worst load case.

Customers should prepare a sketch for each section of the model that is analyzed, showing the forces and moments acting on that section. The analysis of each section should list approximations, assumptions, model section properties, and the heat-treatment condition of the material. All general equations should be listed before numerical values are substituted. Shear and moment diagrams should be given for a worst-case distribution. A sufficient number of model sections should be analyzed to determine allowable shear, axial load, bending stress, and torsion so that the location of the critical model section can be determined.

The model stress report should show that the model, the mounting points, and the restraints are statically and dynamically stable within the model test envelope. The Reynolds number, Mach number, surface conditions, and other parameters used in developing the equations noted in the analysis should be discussed. In addition, the range of mass and inertia parameters and of stiffness coefficients used in the analysis should be noted.

7.3.6 ***Material selection.***—Materials for the model and any support structures must be selected according to the mechanical or electrical properties described in one of the following standards:

(1) Aerospace Structural Metals Handbook
(2) American Institute for Steel Construction (AISC)
(3) American National Standards Institute (ANSI)
(4) American Society for Testing Materials (ASTM)
(5) American Society of Mechanical Engineers (ASME)
(6) American Welding Society (AWS)
(7) Military Handbook #5
(8) National Bureau of Standards (NBS)
(9) National Electrical Code (NEC)
(10) Society of Automotive Engineers (SAE)

All materials properties should be suitably corrected for temperature.

7.3.7 ***Structural joints.***—All counterbores, spotfaces, and countersinks in the model and other support structures must be properly aligned so that no bending is applied to the fasteners by torquing. The minimum safety factor for bolted joints that clamp a model, sting, model auxiliary structure, or model equipment is 4.0 (based on yield stress) and 5.0 (based on ultimate stress) for heat-treated hardened bolts. The safety factors are based on bolt cross-sectional area and not on the tightened, or proof, load (i.e., the maximum load that can be applied to a bolt without obtaining a permanent set, or permanent stretch).

The cross-sectional area of the bolts is determined by first calculating the flange or joint load for the model or the model support system mating parts (1) for a predetermined hydrostatic, or most severe, test condition and (2) at a room-temperature bolting-up condition. The flange or joint load is then divided by the allowable stress (obtained from bolt strength-of-material tables) at the temperature condition determined from step (1) or (2). Allowable stress is defined as the smaller value of either the yield stress or the ultimate stress divided by the appropriate safety factor. The allowable stress from tables such as those found in the ASME Boiler and Pressure Vessel Code (sect. VIII) includes the appropriate safety factor, and further safety factors do not need to be added. The division of the flange or joint load by the allowable stress defines the total cross-sectional area for the bolts. This calculation does not define the tightness or tension required on the bolts.

Current engineering practice requires tightening bolts from 75 to 90 percent of the proof load. The individual bolts will have a safety factor of 1.25 to 1.50 (based on the ultimate stress divided by the proof stress of the material), but the flange or joint will have a much higher safety factor based on the required area.

Thus, when a bolt is properly pretensioned, the bolt load will only increase an incremental amount with a large external load. Consider a nongasketed flat-face joint. If the bolts have a high preload of 90 percent of proof load and then an external load of up to 100 percent of the preload is applied to the bolts, the bolt tension will only increase by a small amount, approximately 10 percent. (The initial joint compressive stress is nearly cancelled by the external tensile stress; see ref. 15). The exact tension increase depends on the compression area and on the relative stiffness between the flange or joint and the bolts. The bolt flange or joint is designed for a safety factor of 3.0 to 5.0 (based on whether the yield or the ultimate stress is the controlling factor). On the basis of these safety factors, the actual bolt stresses will be one-third to one-fifth of the allowable stresses. Because bolt stresses and loads are proportional, the bolt loads will vary from 33 to 20 percent of the allowable loads, whereas the bolt preload will be 90 percent of the proof load. Therefore, if the bolt does not fail during tightening, it will not be likely to fail under static loading conditions; the cyclic, tensile, and thermal loads would still have to be considered.

Shear loads should be transmitted through keys and pins that are properly retained. Welded joints should be designed in accordance with the American Welding Society code. All critical joints—joints whose failure would result in the loss of the model or model components or in damage to the facility—must be x-rayed.

7.3.8 Pressure systems.—Models and support and test equipment that use hydraulic, pneumatic, or other systems with operating pressures above 15 psig must be designed, fabricated, inspected, tested, and installed in accordance with the ASME Boiler and Pressure Vessel Code (section VIII), the American Standards Association (ASA) codes of the ASME, and/or Department of Transportation (DOT) regulations. Pressure vessels are all shells, chambers, tanks, or components that transmit a gas at pressures exceeding 15 psig. Pressure vessels must be welded in accordance with the ASME Boiler and Pressure Vessel Code. (See section IX of the code for welding qualifications and section V for nondestructive inspection.)

Pressure relief devices may be required in a hydraulic or pneumatic system but not necessarily in the model. These devices must be able to relieve overpressure by discharging sufficient flow from the pressure source under conditions that cause malfunctions.

For pressure systems, the following information on all components should be available to the facility manager and the FTED project engineer: volume capacity, temperature range, working pressure, and proof test pressure. All pressure system components should be stored in a clean, dry, and sealed condition after proof testing and before delivery to the 1×1 SWT.

7.3.9 Pressure piping.—All piping must be designed, fabricated, inspected, tested, and installed in compliance with the latest edition of the ANSI/ASME Standard Piping Code. Powered models have internal piping that falls under this code. Pressure vessels that are constructed from standard pipe fittings and standard flanges are also considered pressure piping and use the ANSI/ASME Standard Piping Code.

Pressure piping must be welded according to the procedures outlined in section IX of the ASME Boiler and Pressure Vessel Code and in the ANSI Standard Piping Code. All service lines into and out of the model should be properly identified with the working pressures, the flow direction, and the fluid or gas being carried.

7.3.10 Electrical equipment components.—In the facility test section, only qualified hardware, equipment, and material conforming to the National Electrical Code should be used. All pressure transducers, strain gauges, vibration pickups, and other low-voltage devices should use shielded cable. Details regarding customer-supplied control panels plus the associated wiring to the facility control room and electrical wiring diagrams and connectors at interfaces located at control boxes and/or at the model should be discussed with FTED project engineer and the facility electrical engineer at one of the pretest meetings.

7.4 Model Fabrication Requirements

Models should be completely assembled at the manufacturer's plant. All model parts must be inspected to ensure proper fit and must be certified for the required loads and deflections during testing. All remotely controlled model functions should be checked out, and position indicators should be calibrated before the model is shipped to Glenn. After the model is installed in the tunnel test section, a final end-to-end check of all instrumentation and a final calibration of all remotely controlled model functions will be made.

All electrical leads and pneumatic lines from the model should be clearly identified. In addition, the pneumatic lines should be cleaned and free of oil and debris. They should be checked for leaks at operating pressures. End-to-end checks are required for the model's electrical and pneumatic systems.

7.5 Quality Assurance Requirements

Written procedures for model assembly, installation, and configuration changes in the 1×1 SWT test section should be submitted to the FTED project engineer at least 8 weeks prior to tunnel tests. These procedures should include the sequential steps that are to be taken to install the model in the tunnel test section along with the necessary drawings. In addition, bolt torquing values for fastening the model to its support structure should be given, and the assembly, installation, and checkout of user-supplied hardware should be addressed.

8.0 General Information

The following information is provided to familiarize customers with services available and standard operating procedures at the 1×1 SWT.

8.1 Support

8.1.1 Model buildup.—Models to be tested in the 1×1 SWT must be assembled prior to arrival at Glenn. There may be occasions where some model work will be required prior to installation of the model in the tunnel test section. Customers should discuss with the facility manager and the FTED project engineer the appropriate arrival time for the model and any other user-supplied auxiliary equipment.

8.1.2 User responsibility.—It is advantageous for customers to supply technicians to assist with complex model installations. Customers must supply all tools, spare parts, special equipment, and supplies necessary to perform work on the model. A test engineer familiar with the model and the test objectives should be onsite during the test.

8.1.3 Operation of Government equipment.—Customers should not operate Government-furnished equipment or make connections to this equipment without the approval of Glenn personnel.

8.1.4 Tunnel safety.—During the time that the tunnel is shutdown and the model is being examined, care should be exercised to avert injury from sharp model edges (if they exist). Customers should provide guards for all exposed instrumentation rakes and for sharp model edges, spikes, and tips.

8.1.5 Support during tests.—All requests for manpower assistance, shop, or facility services should be directed to the FTED project engineer.

8.2 Operations

8.2.1 Nominal operating days and shift hours.—Tests are usually supported on the day shift, from 9:00 a.m. to 5:00 p.m. EST, Monday through Friday. Every other Monday is usually a facility maintenance day, and testing does not take place.

8.2.2 Off-shift coverage.—Test hours other than those noted may be possible. Scheduling tests for and accessing the 1×1 SWT at times other than the day shift must be coordinated with the FTED project engineer.

8.3 Planning

8.3.1 Safety requirements.—The following conditions require special action to be taken by the Facility Safety Committee:

(1) Experiments using radioactive materials or gases
(2) High-speed rotating parts without suitable shrouds
(3) Ejection of materials or gases that could cause an explosion
(4) Use of toxic materials (a material safety data sheet must be provided by customers)

8.3.2 Test time.—For non-NASA users, tunnel test time charged to an experiment includes the total time that the facility is available to customers. This time includes model and instrumentation installation, experiment time, model removal and crating for return shipment, and return of the tunnel and associated areas to their pretest conditions. Extensions to a test window can be negotiated between the customer's lead engineer and the facility manager. Discussions with NASA personnel who have used the facility should help customers make fairly accurate estimates of the time required to complete test programs.

8.3.3 NASA debriefing.—Near the completion of the test program, the customer's lead engineer will meet with the facility manager to evaluate the test program. The facility manager will make arrangements for this meeting.

8.4 Security

The advance notice required to obtain access to the 1×1 SWT depends on the classification of the test program and the category of the NASA visitor. During nonclassified test programs, the FTED project engineer will notify Glenn's Visitor Control Center at least 3 days before the arrival of a non-NASA visitor who is a U.S. citizen. The project engineer will need the person's name and place of employment, as well as the date and purpose of the visit. Non-U.S. citizens should make arrangements with their embassies in Washington, D.C., prior to their intended visits to Glenn. The appropriate embassy should work with NASA Headquarters in Washington, D.C., to establish the necessary clearances.

For sensitive test programs, the proper security clearance must be in place prior to the arrival at Glenn of a non-NASA visitor who is a U.S. citizen. Glenn's Security Office requires the receipt of a visit notification letter from each visitor's company. This letter must include the following information for each visitor:

(1) Social Security Number
(2) Full name
(3) Date and place of birth
(4) Security clearance level
(5) Date clearance was granted
(6) Person who granted the clearance
(7) Date and duration of the visit
(8) NASA contact

Visit notification letters should be sent to

National Aeronautics and Space Administration
John H. Glenn Research Center
Lewis Field
Attn: Security Office, MS 21–5
21000 Brookpark Road
Cleveland, Ohio 44135
Phone: (216) 433–3062
Fax: (216) 433–6664

The FTED project engineer will notify Glenn's Security Office and Visitor Control Center 3 days before the arrival of non-NASA visitors who want to participate in a sensitive test program at the Center.

Appendix A
Symbols

$A/A*$	ratio of local cross-sectional area of an isentropic stream tube to cross-sectional area at a point where $M = 1$, dimensionless
a	acoustic speed, ft/sec
g_c	gravitational constant, 32.2 $(\text{ft-lb}_m)/(\text{lb}_f\text{-sec}^2)$
M	Mach number, dimensionless
P_s	static pressure, psfa
R	gas constant for air, 53.35 $(\text{ft-lb}_f)/(\text{lb}_m\text{-°R})$
Re/L	Reynolds number per unit length, (1/ft)
S	Sutherland constant, 198.6
T_r	reference static temperature, 518.6 °R
T_s	static temperature, °R
T_T	total temperature, °R
V	velocity, ft/sec
γ	ratio of specific heats, (equal to 1.4 when air is treated as a completely perfect gas), dimensionless
ρ_s	static density, lb_m/ft^3
μ_r	reference dynamic viscosity of air at 518.6 °R, 1.213310^{-5} $\text{lb}_m/(\text{ft-sec})$
μ_s	dynamic viscosity of air based on static temperature, $\text{lb}_m/(\text{ft-sec})$

Appendix B
Contact Person

The facility manager is the key contact person at the 1×1 SWT. Mail correspondence should be addressed as follows:

National Aeronautics and Space Administration
John H. Glenn Research Center
Lewis Field
Attn: 1×1 SWT Facility Manager,[a] MS 6–8
21000 Brookpark Road
Cleveland, Ohio 44135

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[a] The name of the 1×1 SWT facility manager can be obtained from a Glenn telephone directory. This information is presented in the organizational listing under Facilities and Test Engineering Division, Facility Management and Planning Branch (organizational code 7502). In the absence of a directory, call (216) 433–4000 (Glenn switchboard operator) and ask for the name of the facility manager.

Appendix C
Reynolds Number per Unit Length Calculations

The dynamic viscosity of air using static temperature is given by the following equation:

$$\mu_s = \mu_r \left(\frac{T_s}{T_r} \right)^{1.5} \left(\frac{T_r + S}{T_s + S} \right) \tag{C1}$$

The equation of state for air treated as a perfect gas is

$$P_s = \rho_s R T_s \tag{C2a}$$

or

$$\rho_s = \frac{P_s}{R T_s} \tag{C2b}$$

The velocity of air is given by

$$V = M\, a \tag{C3}$$

The acoustic speed is given by

$$a = \left(\gamma g_c R T_s \right)^{0.5} \tag{C4}$$

The Reynolds number per unit length is given by

$$\frac{\mathrm{Re}}{L} = \frac{V \rho_s}{\mu_s} \tag{C5}$$

Substitute equations (C1), (C2b), (C3), and (C4) into equation (C5) and obtain the following:

$$\frac{Re}{L} = M \left(\gamma g_c R T_s \right)^{0.5} \frac{P_s}{R T_s} \frac{1}{\mu_r} \left(\frac{T_r}{T_s} \right)^{1.5} \left(\frac{T_s + S}{T_r + S} \right) \tag{C6}$$

Combine similar terms in eq. (C6) and obtain the following equation:

$$\frac{Re}{L} = M \left(\frac{\gamma g_c}{R} \right)^{0.5} \frac{1}{\left(T_s \right)^2} P_s \frac{1}{\mu_r} \left(T_r \right)^{1.5} \left(\frac{T_s + S}{T_r + S} \right) \tag{C7}$$

Substitute constant values from the symbol list (app. A) into equation (C6) and obtain the following expression:

$$\frac{\mathrm{Re}}{L} = 1.248 \times 10^{6} \left(P_s M \right) \left[\frac{T_s + 198.6}{\left(T_s \right)^2} \right] \tag{C8}$$

and

$$T_s = \frac{T_T}{1 + \frac{\gamma - 1}{2} M^2} \tag{C9}$$

Table V presents the maximum and minimum Reynolds numbers per unit length as computed by equation (C8).

Appendix D
Summary of Procedure for Obtaining Test Time

(1) Customer contacts the 1×1 SWT facility manager and submits the overall test requirements at least 4 to 6 months before the test.

(2) Facility manager and appropriate Facilities and Test Engineering Division (FTED) personnel review the request.

(3) Customer submits a formal letter of request to the Director of Engineering and Technical Services at Glenn (for non-NASA requestors only).

(4) If the project is accepted, a test agreement is prepared and signed (for non-NASA requestors only).

(5) A series of pretest meetings are held at Glenn to discuss the test plan, the instrumentation, the tunnel hardware, and the data requirements. Attendees are the requestor and his or her key personnel, the facility manager, appropriate FTED branch chiefs, key FTED personnel, and the FTED project engineer.

Appendix E
Summary of Requirements for Pretest Meetings

A series of pretest meetings are held at Glenn to discuss the test plan, the instrumentation, the tunnel hardware, and the data requirements. Attendees are the requestor and his or her key personnel, the facility manager, appropriate FTED branch chiefs, key FTED personnel, and the FTED project engineer. Because the laser system is a shared resource, customers should notify the facility manager at least 6 months before they will need this equipment.

Customers Must Bring the Following Items to the Pretest Meetings (at least 8 weeks before the start of a program)

- Requirements document that indicates the test objectives and goals, and thoroughly explains any special test procedures (bring to first meeting)
- List of requested instrumentation
- Written computing instructions
- Any requests for customized output and computed results (data input, data output, and equation sets in engineering language) if Glenn is to perform the data reduction
- Written procedures for model assembly, installation, and configuration changes in the 1×1 SWT test section
- Prioritized run schedule that is compatible with the available test window (prepared by customer's project engineer)
- Drawings of the model installation in the facility test section
- Test envelope for the model
- Loading on the model—Mach number, dynamic pressure, and model attitude
- Model stress report that is part of a model systems report (should include stress analysis based on the maximum loads that are anticipated on all sections of the model, per criteria in section 7.3.5)
- Detailed drawings of the cross-sectional area distribution of the model to allow blockage and air load calculations
- Drawings that show model installation and model support systems
- All calibration information that is to be supplied by customers
- List of all customer-supplied equipment plus block diagrams and wiring schematics
- Selected model drawings and/or photographs for reproduction in NASA technical papers (if the customer and Glenn agree that it would be mutually beneficial)

Items to Discuss at Pretest Meetings

- Security
- Video and still camera setups
- Probe Actuator Control System (PACS) capabilities
- Detailed information on the length of the thermocouple leads
- Escort D Program availability
- Conversion of data to digital tape with the analog frequency-modulated (FM) demultiplexer equipment in the RAC
- Detailed drawings of the nozzle block section, the test section, and the transition section
- Any necessary meetings between customers and CSD computer specialists. These meetings, which establish ground rules for writing the computing requirements, are set up by the FTED project engineer.
- Use of a self-contained, customer-provided computer system for data processing
- Details regarding customer-supplied control panels plus the associated wiring to the facility control room and electrical wiring diagrams and connectors at interfaces located at control boxes and/or at the model

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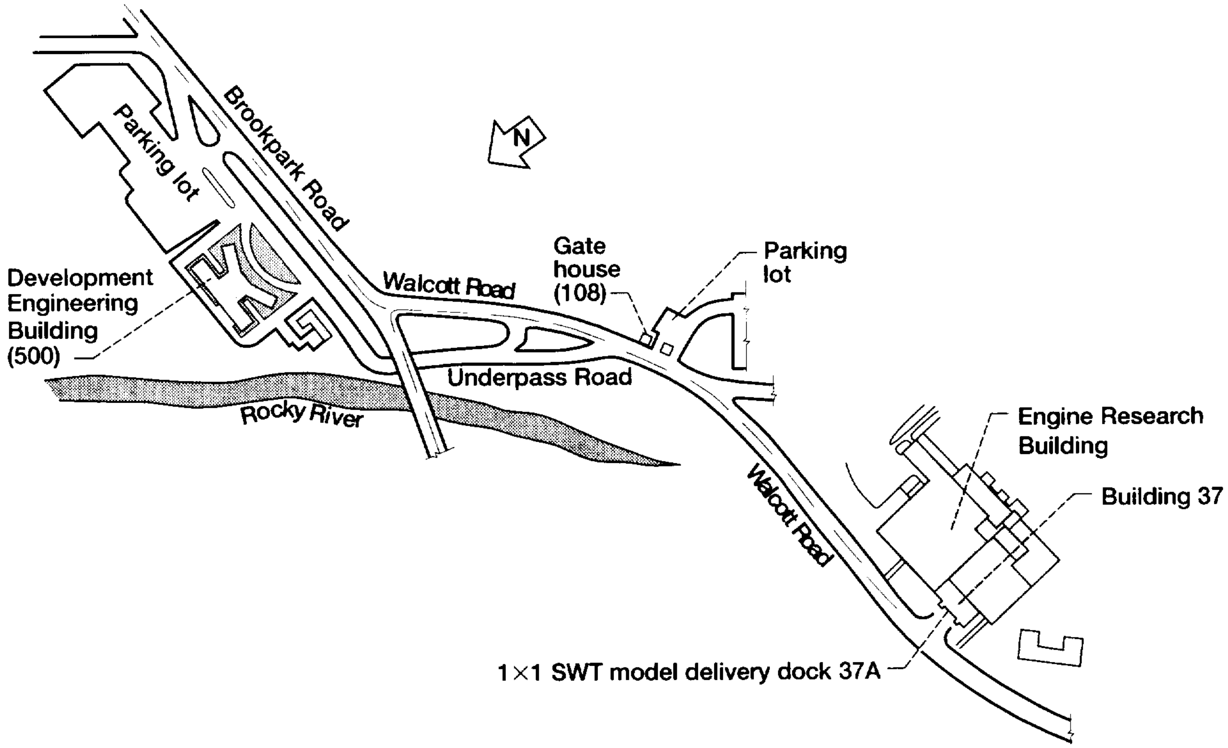


Figure 1.—Directions to 1- by 1-Foot Supersonic Wind Tunnel (1×1 SWT). Note: Underpass road is an alternative entrance to Glenn, but large trucks have a height restriction passing beneath Brookpark Road.

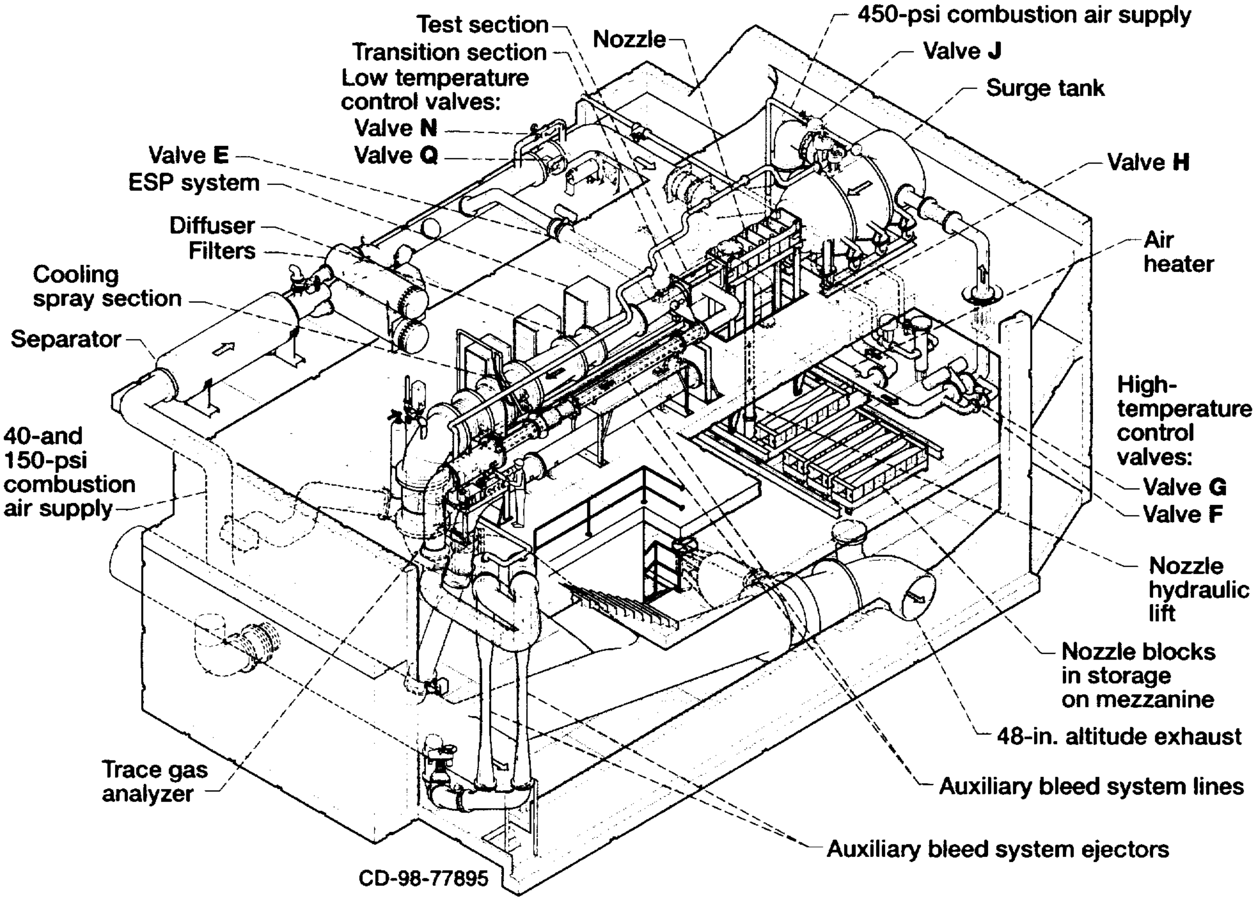


Figure 2.—1- by 1-Foot Supersonic Wind Tunnel. Mach 1.3 to 6.0 (discrete Mach number); maximum pressure, 165 psia; maximum temperature, 1110 °R; Reynolds number per unit length, 0.36 to 20.2x10^6/ft.

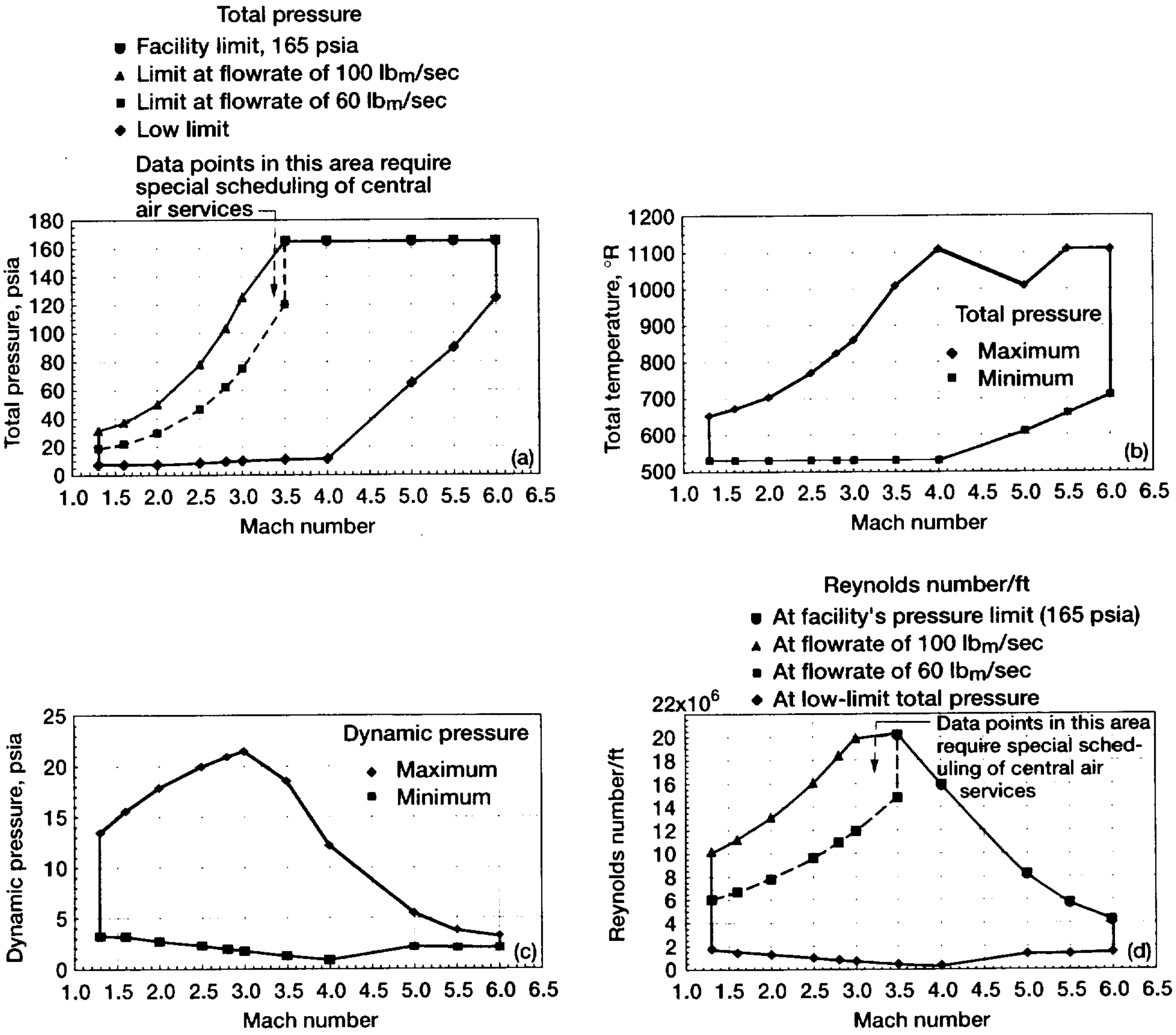


Figure 3.—Operating envelopes for 1- by 1-Foot Supersonic Wind Tunnel. Note that points within the envelopes shown in figures 3(a) to (d) are only possible at the discrete Mach numbers. (a) Total pressure map. (b) Total temperature map. (c) Dynamic pressure map. (d) Map of Reynolds number per foot.

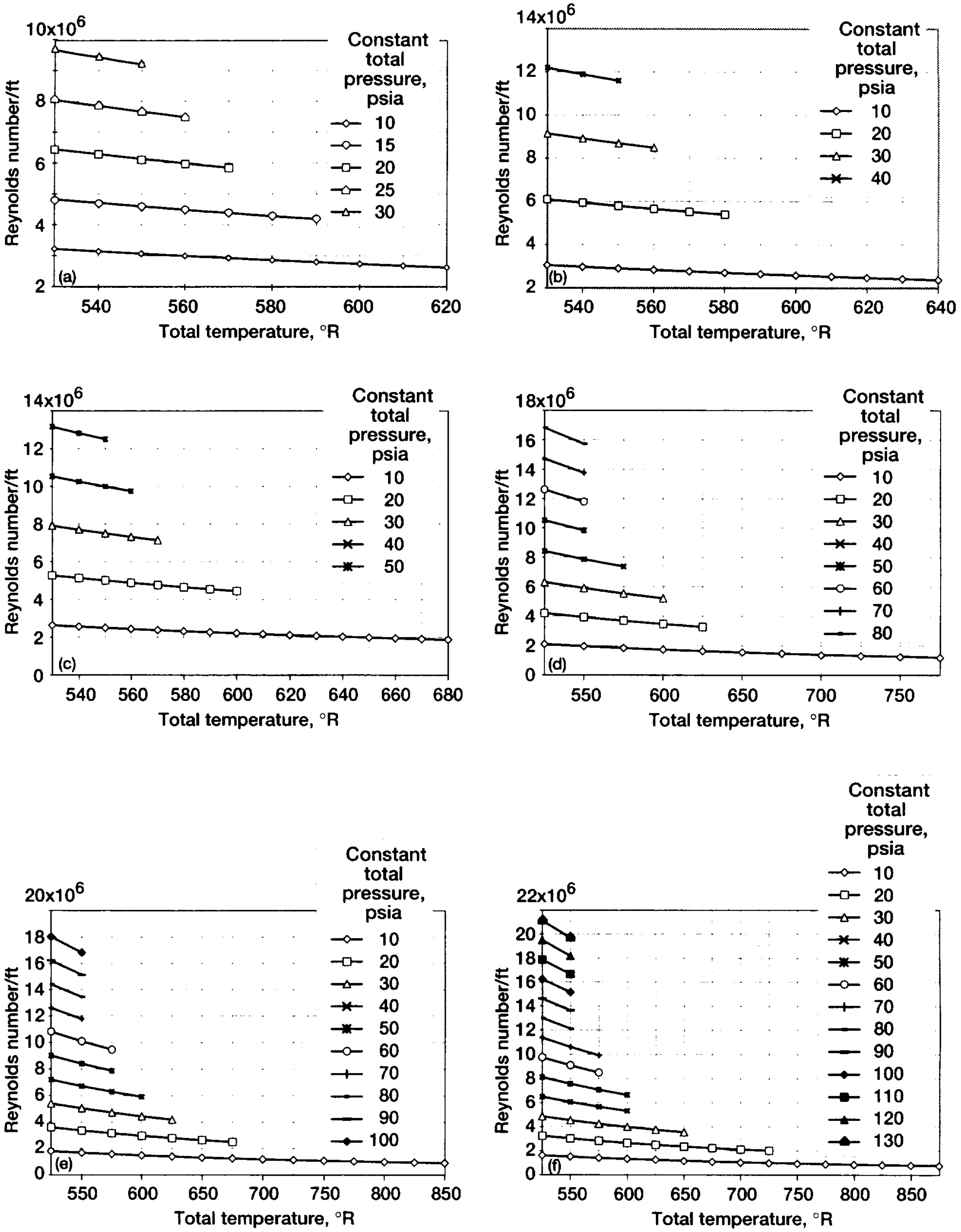


Figure 4.—Maps of Reynolds number per foot as a function of total temperature for each Mach block at selected values of constant total pressure. (a) Mach 1.3. (b) Mach 1.6. (c) Mach 2.0. (d) Mach 2.5. (e) Mach 2.8. (f) Mach 3.0.

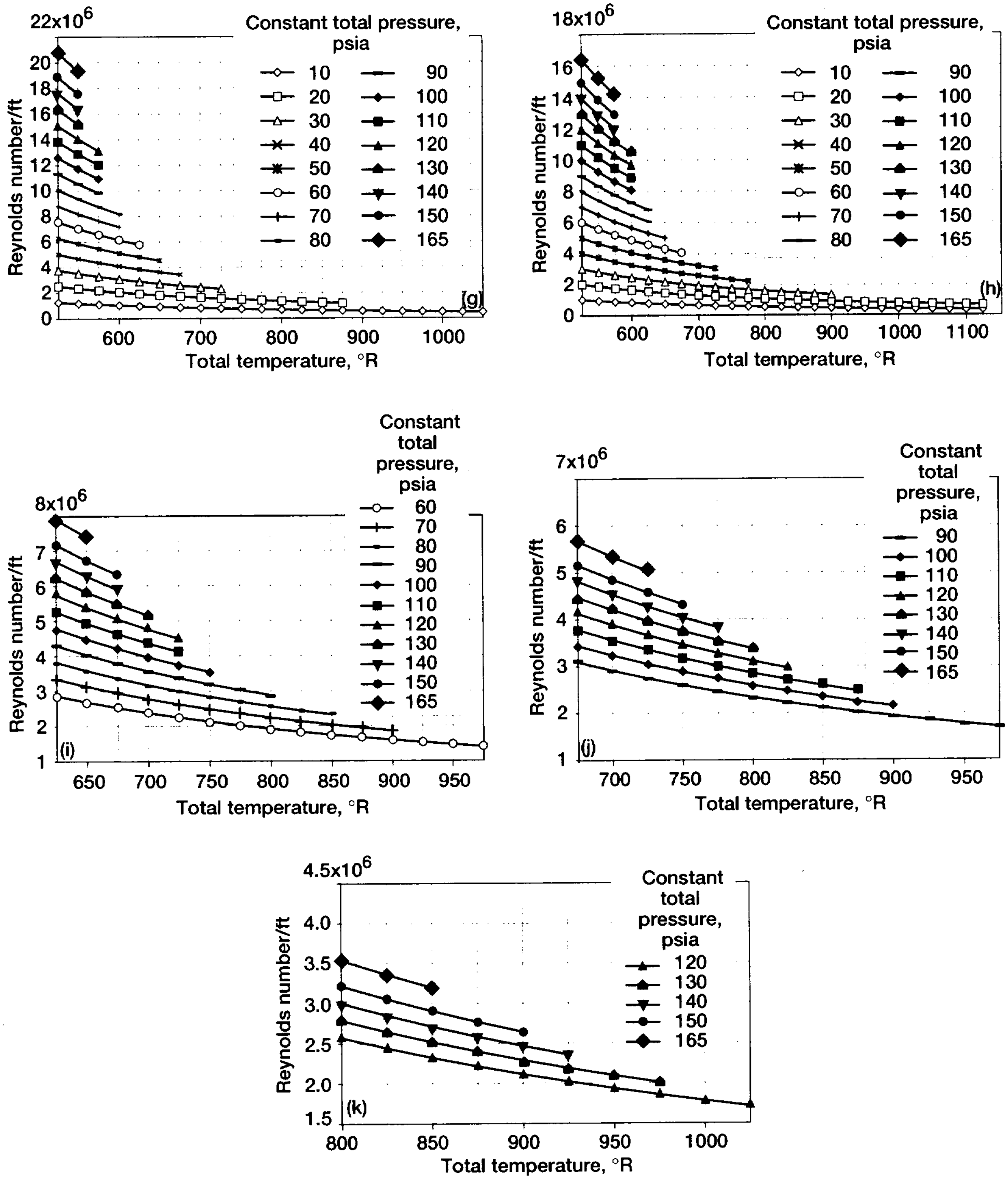


Figure 4.—Continued. (g) Mach 3.5. (h) Mach 4.0. (i) Mach 5.0. (j) Mach 5.5. (k) Mach 6.0.

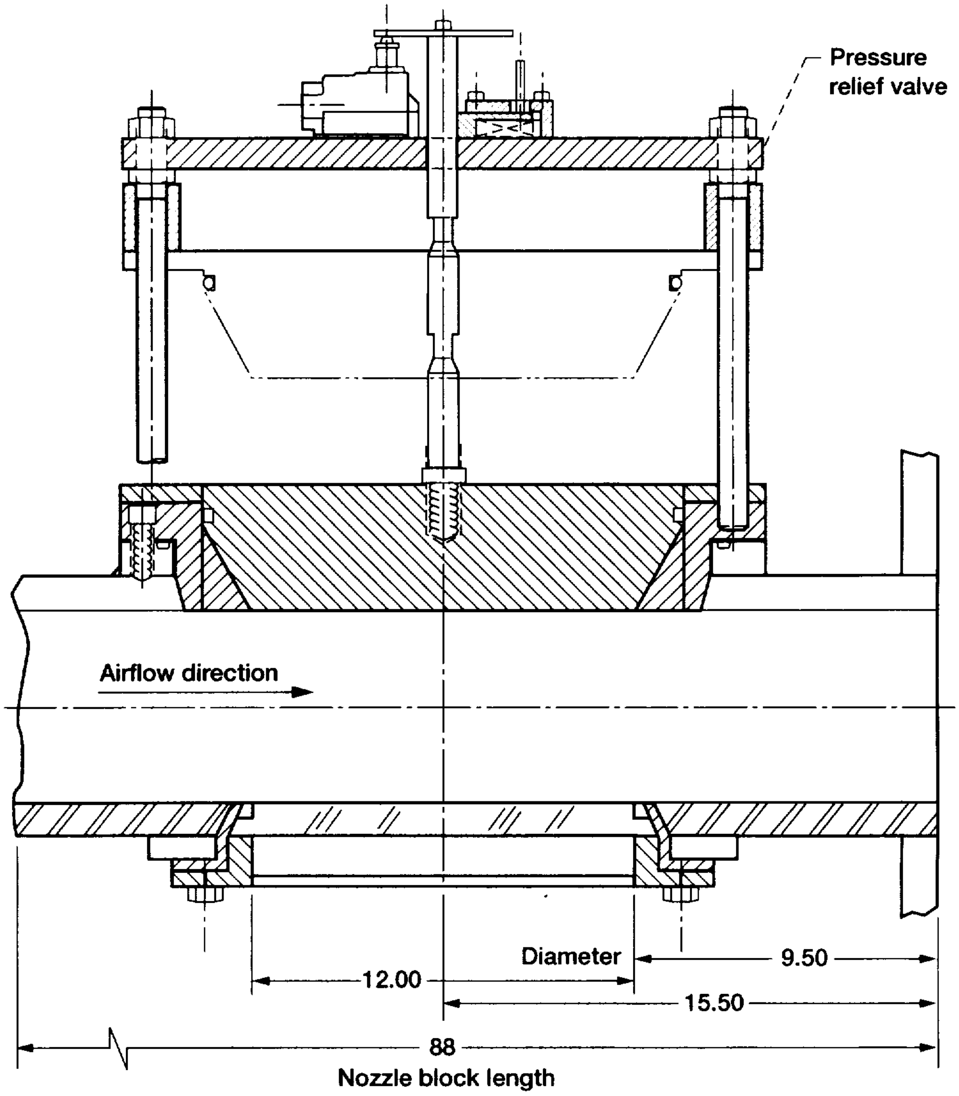


Figure 5.—Elevation view of nozzle block section. All dimensions are in inches.

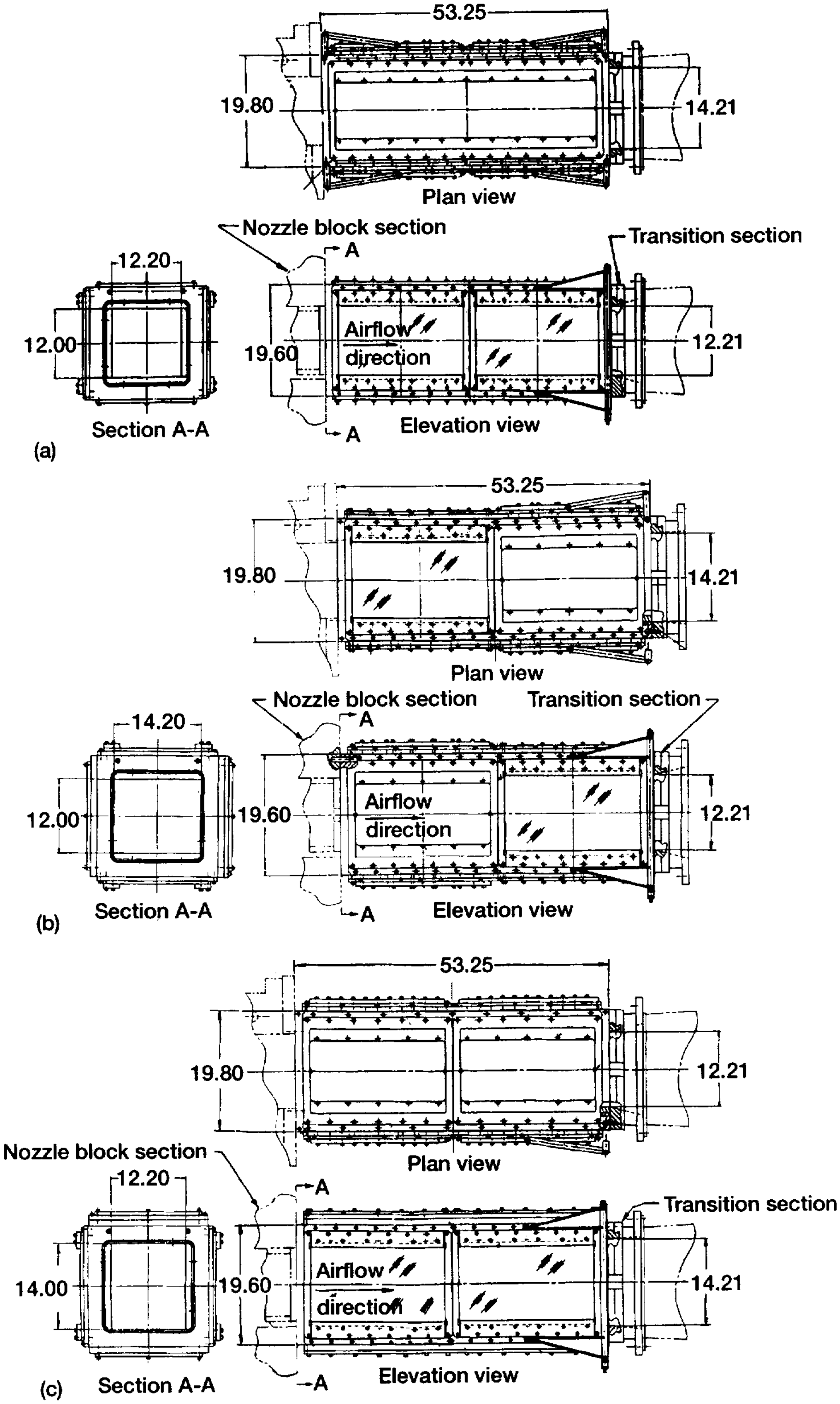


Figure 6.—New test section. All dimensions in inches. (See ref. dwg. 28308M43A000, sheets 1, 3, and 4, available from the project engineer.) (a) 12.00-in.-high, 12.20-in.-wide, short wall configuration (see sheet 1 of 4). (b) 12.00-in.-high, 14.20-in.-wide, horizontally expanded wall configuration (see sheet 3 of 4). (c) 14.00-in.-high, 12.20-in.-wide, vertically expanded wall configuration (see sheet 4 of 4).

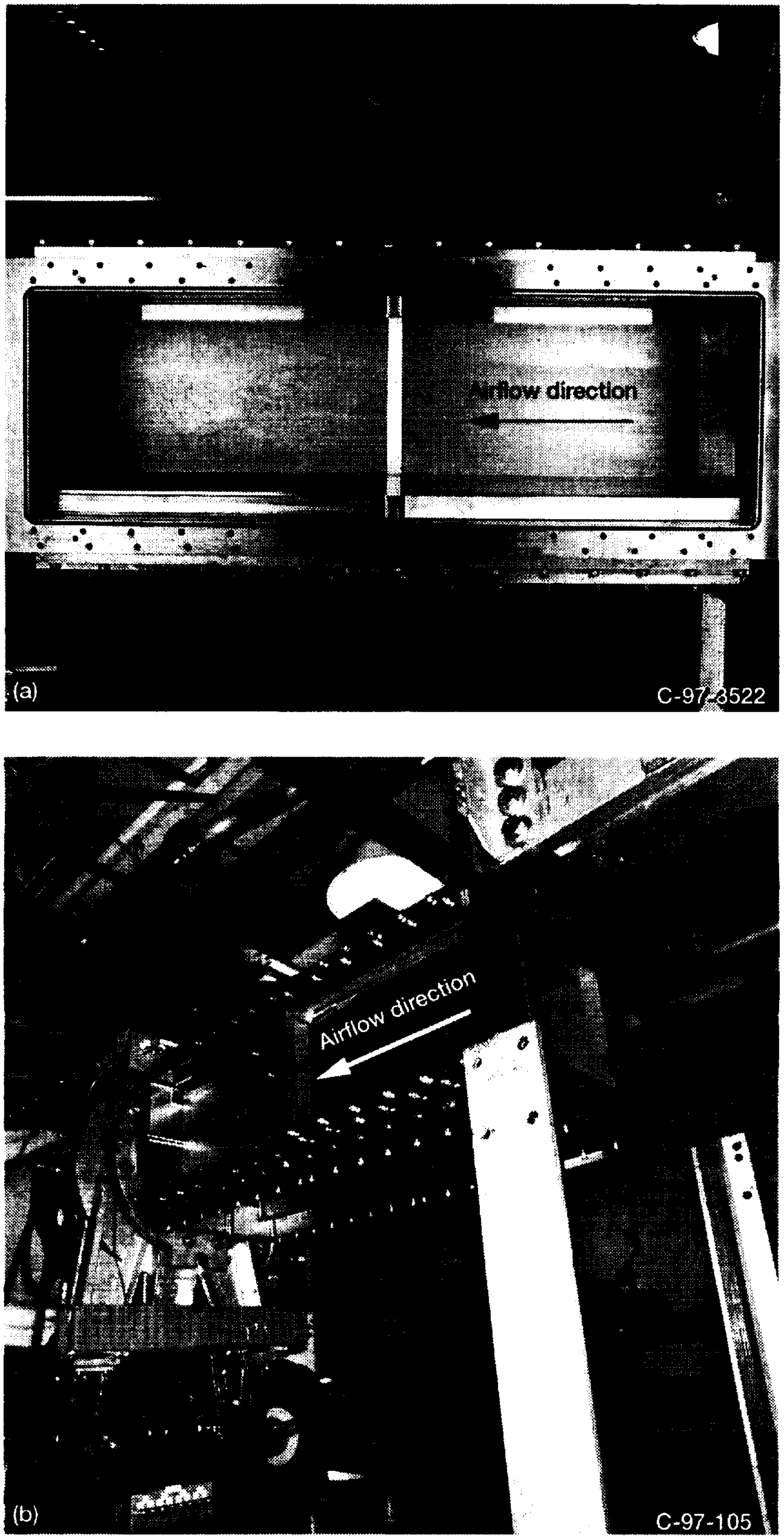
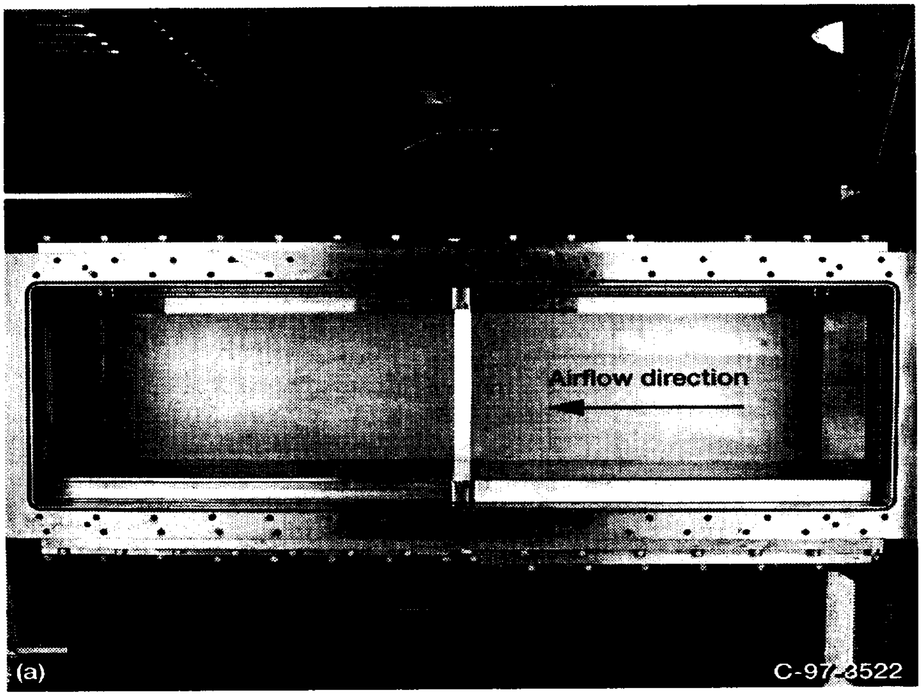


Figure 7.—Test section installed in the 1- by 1-Foot Supersonic Wind Tunnel. (a) Elevation view on the west side of the test section. (b) Viewed from the west side of the test section.


Airflow direction
(a)
C-97-3522


Airflow direction

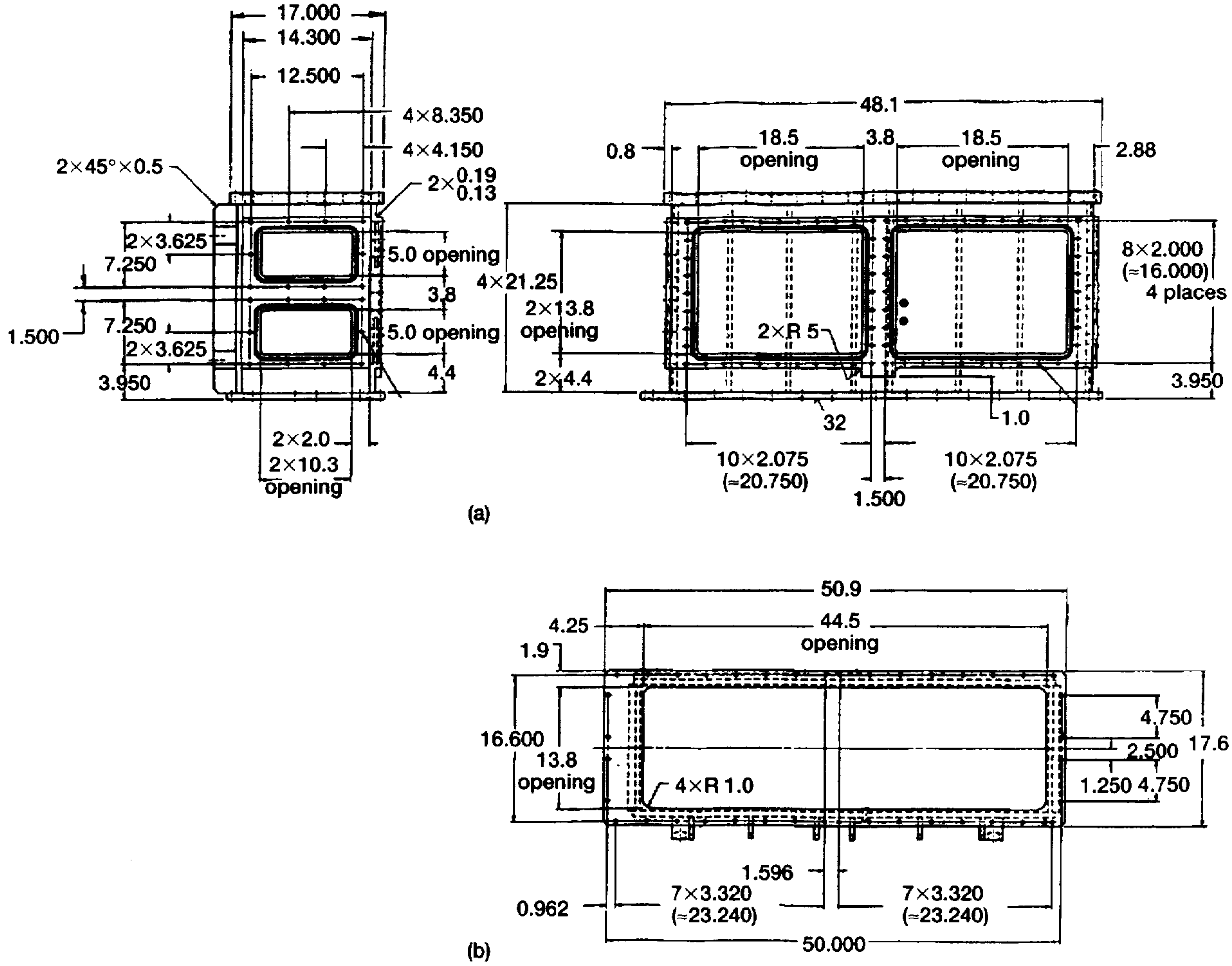


Figure 9.—Exhaust Plenum. All dimensions are in inches. (See ref. dwg. R-58005M77A112 for details, available from the project engineer.) (a) Plan view. (b) Elevation view.

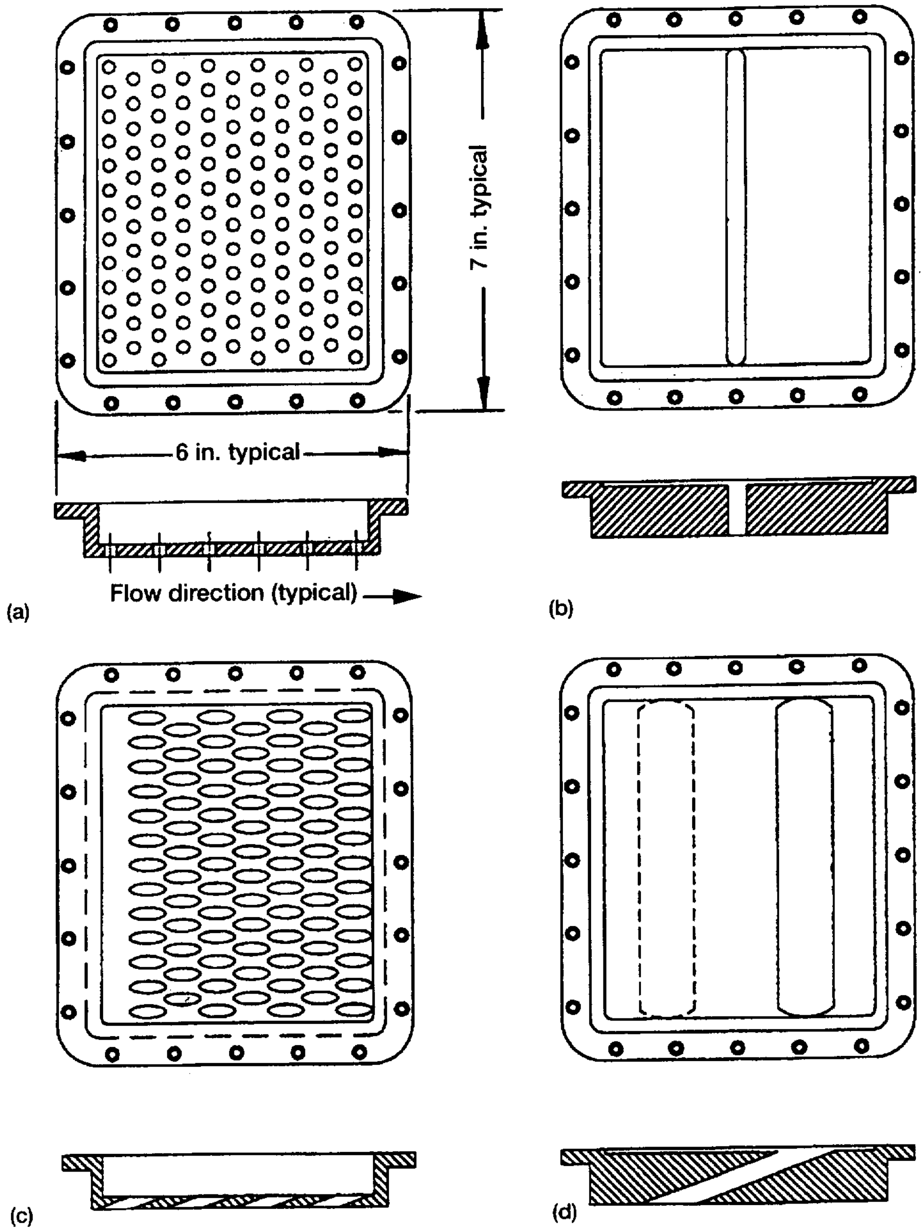


Figure 10.—Test section sidewall bleed plate. (a) Normal hole bleed plate. (b) Normal slot bleed plate. (c) Slanted hole bleed plate. (a) Slanted slot bleed plate.

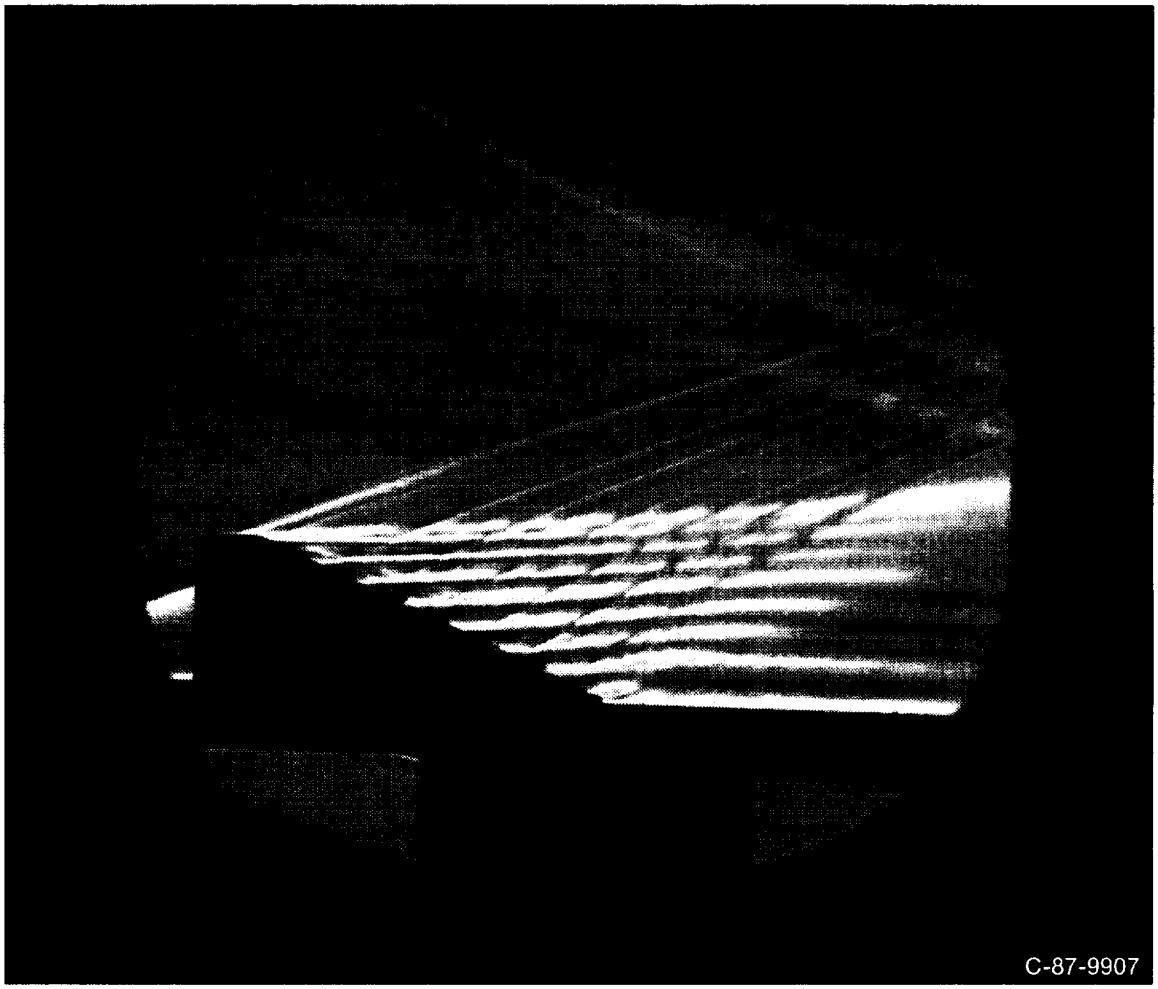


Figure 11.—Schlieren photograph of isolation boundary layer simulator at Mach 4.0. Flow is from left to right.

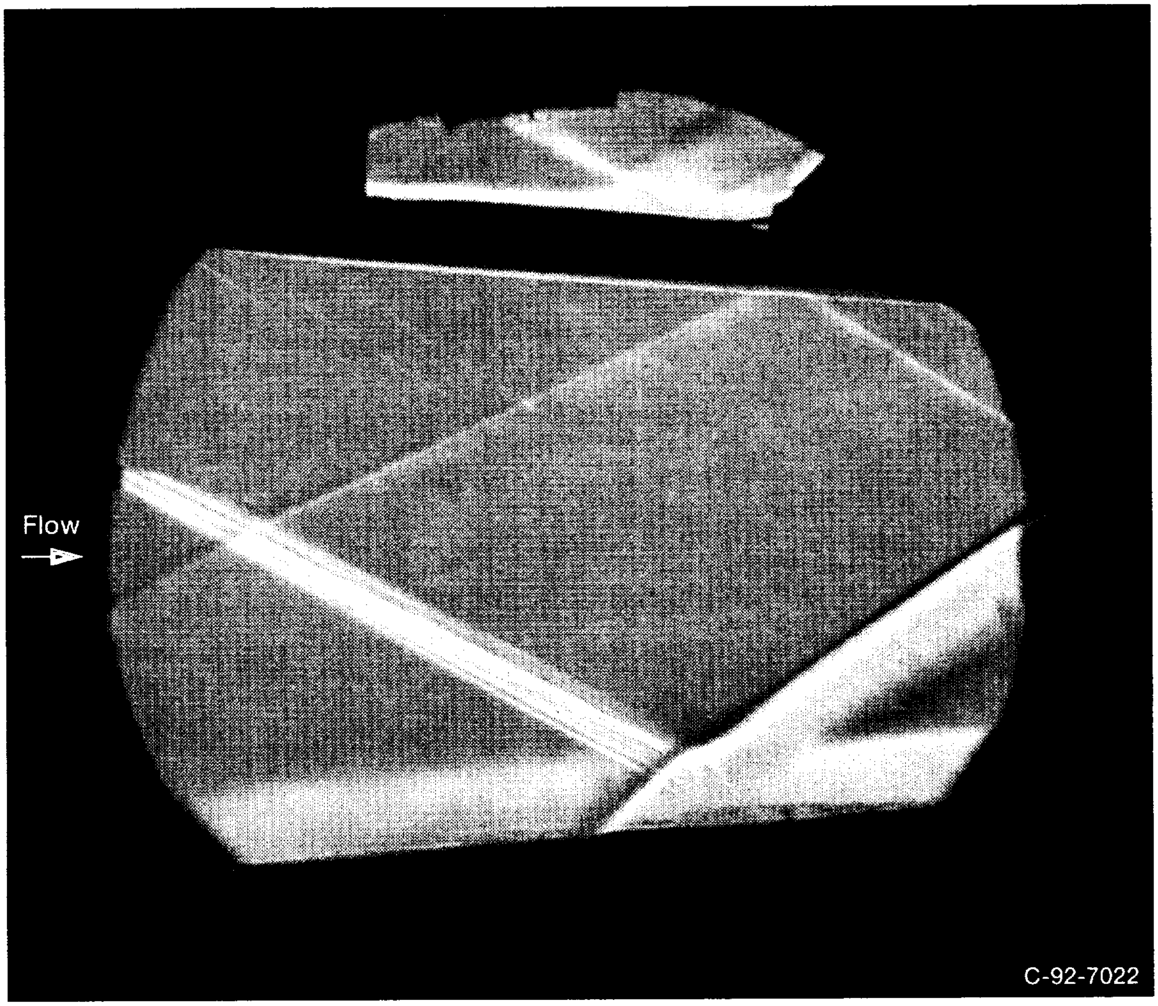


Figure 12.—Schlieren photograph of reflected oblique-shock/boundary layer interaction at Mach 2.5 with shock plate inclined 8°.

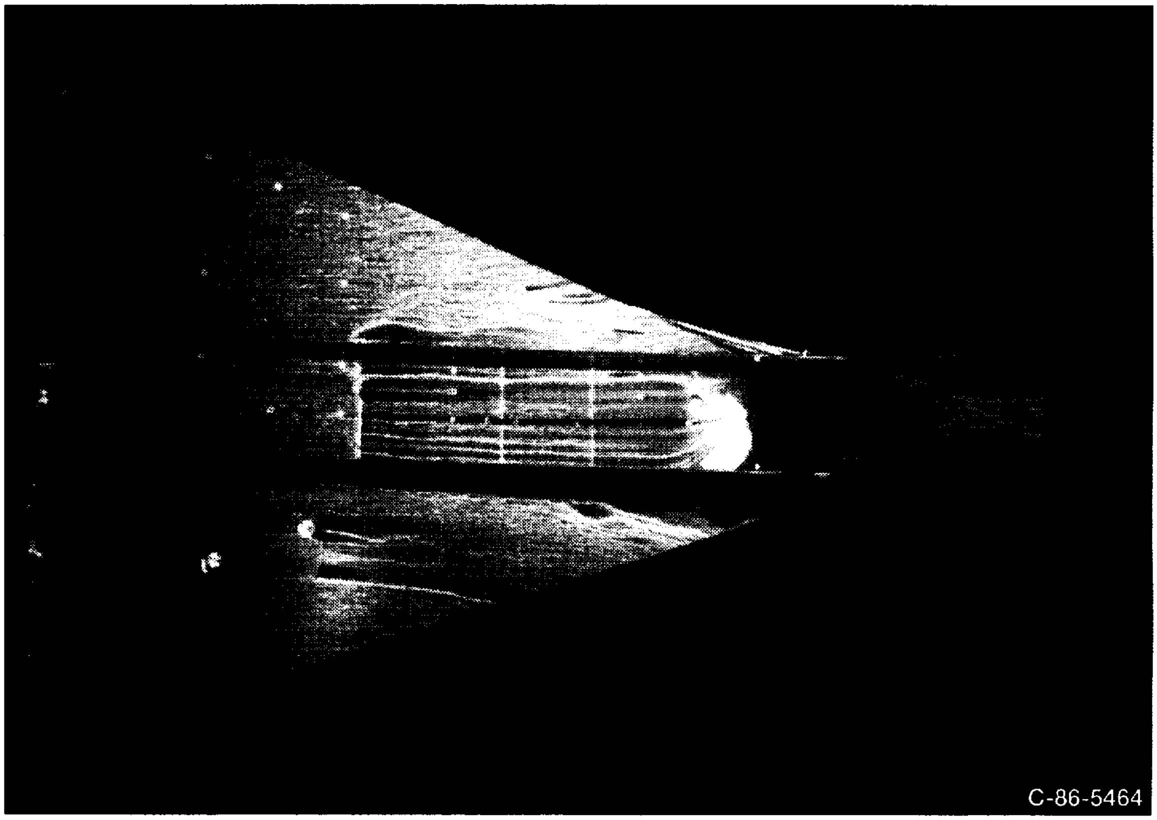


Figure 13.—Plan view of oil flow visualization for Mach 5 inlet model. Test section is at Mach 2.5, and the model is inclined 0° to the flow direction, which is from left to right.

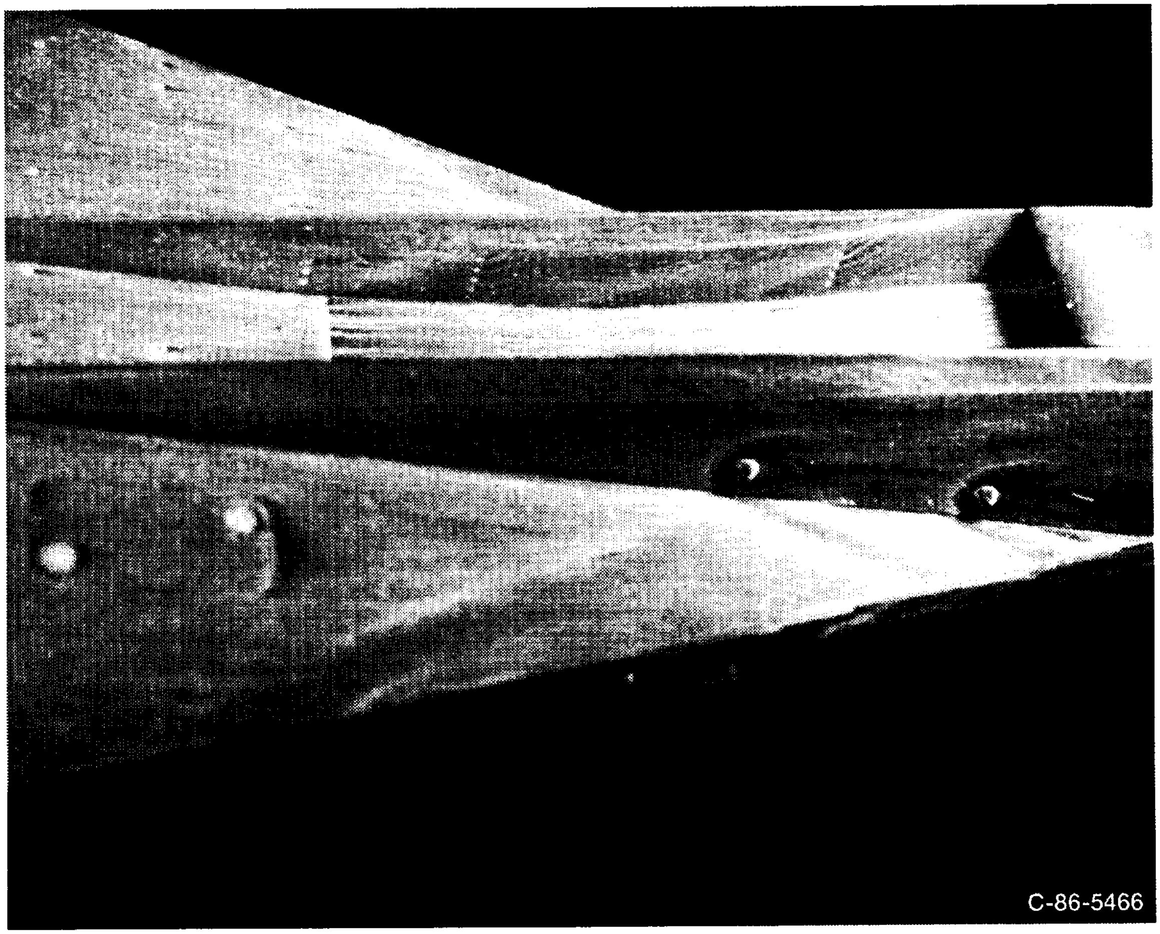


Figure 14.—Elevation view of oil flow visualizaton for Mach 5 inlet model. Test section is at Mach 3.5, and the model is inclined –8.55° to the flow direction, which is from left to right.

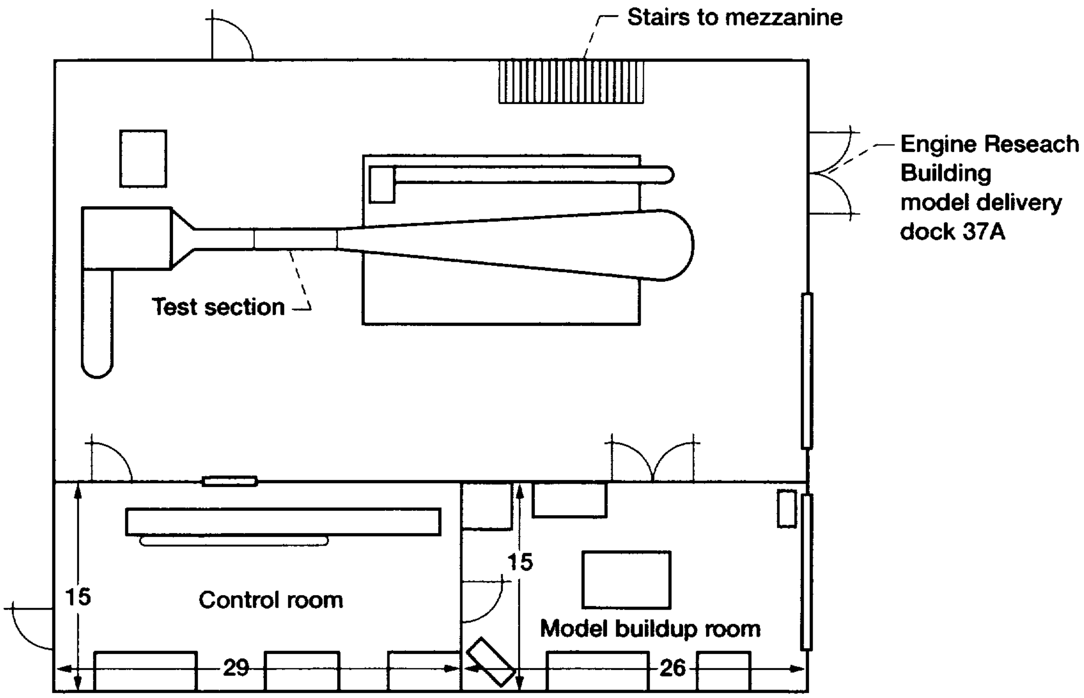


Figure 15.—Floor plan for the 1- by 1-foot Supersonic Wind Tunnel Facility, control room, and model preparation area. All dimensions are in feet.

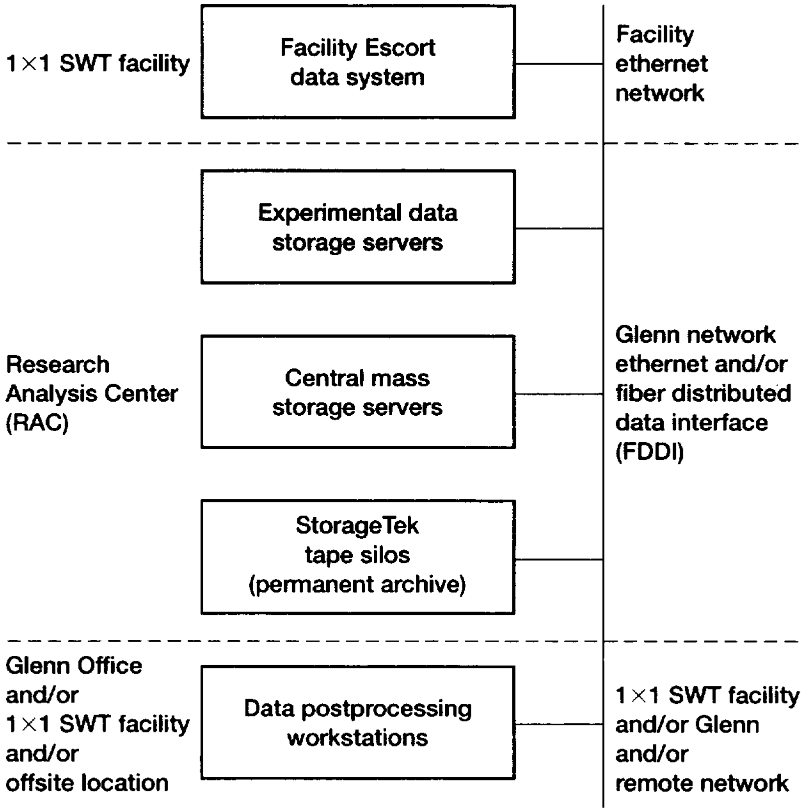


Figure 16.—Overall Escort experimental data processing environment for 1- by 1-Foot Supersonic Wind Tunnel (1×1 SWT).

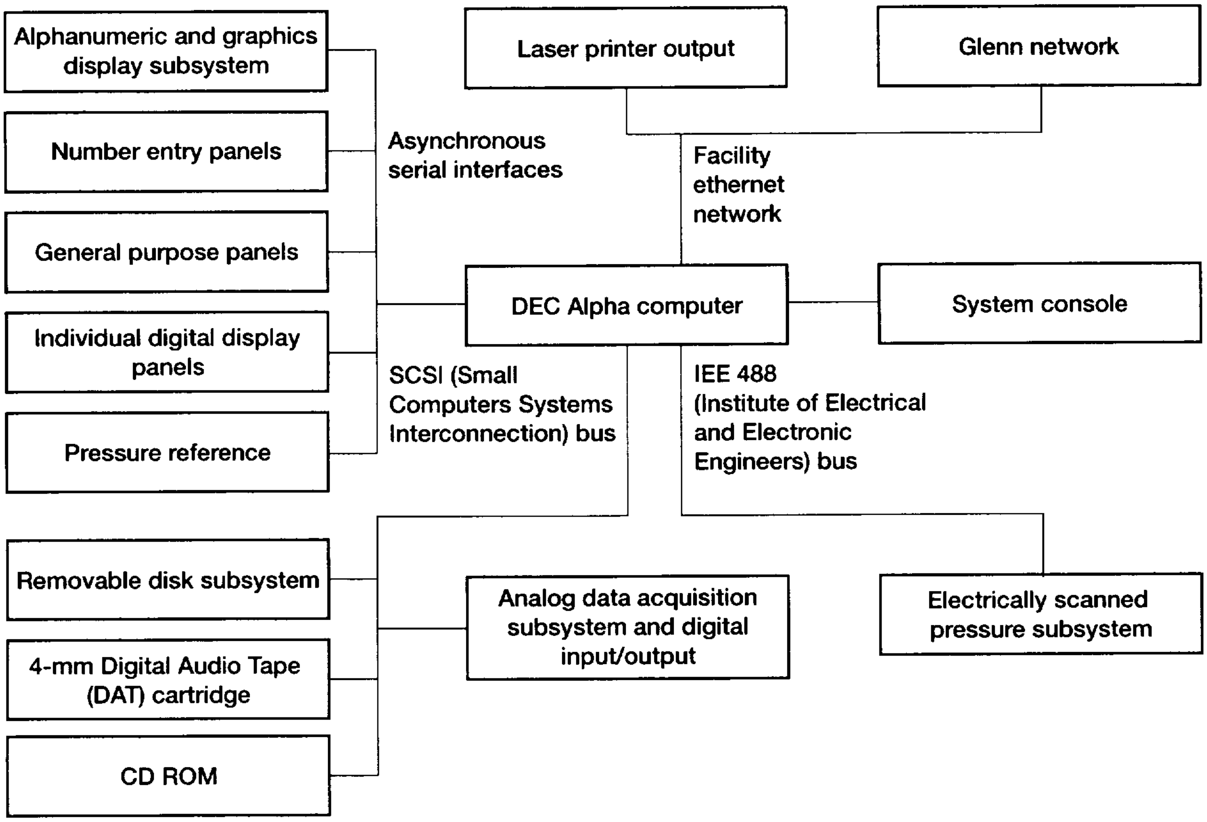


Figure 17.—Escort facility system configuration.

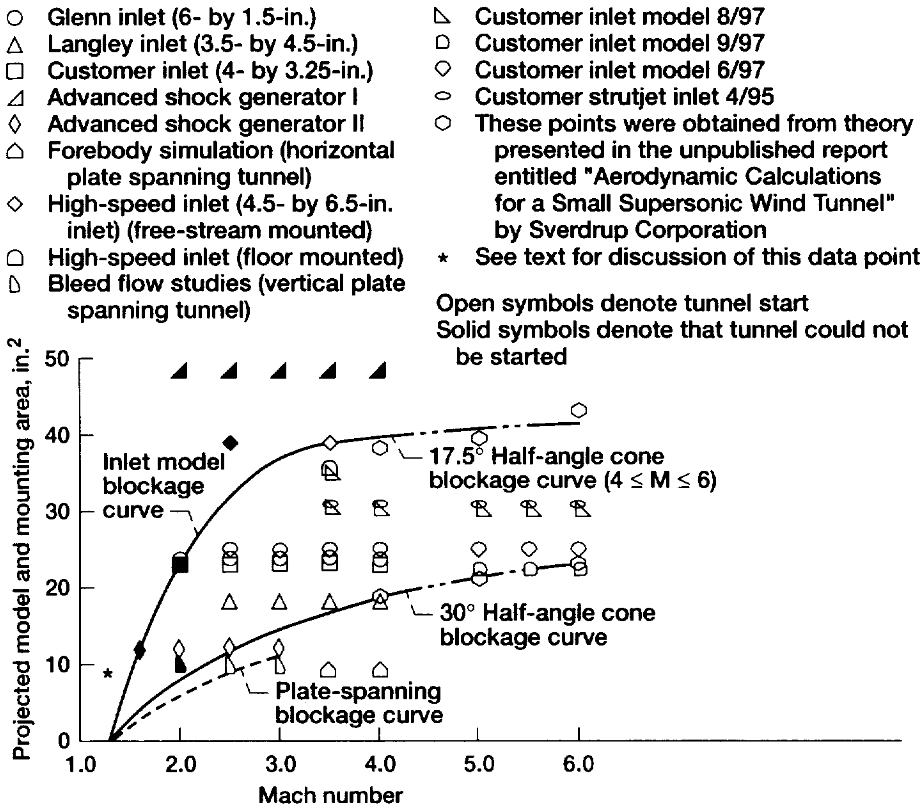


Figure 18.—Model blockage data. Tunnel starting is very dependent on model geometry and position. Therefore, these data should be used only as a guide. (Model inlet sizes are listed here for reference).

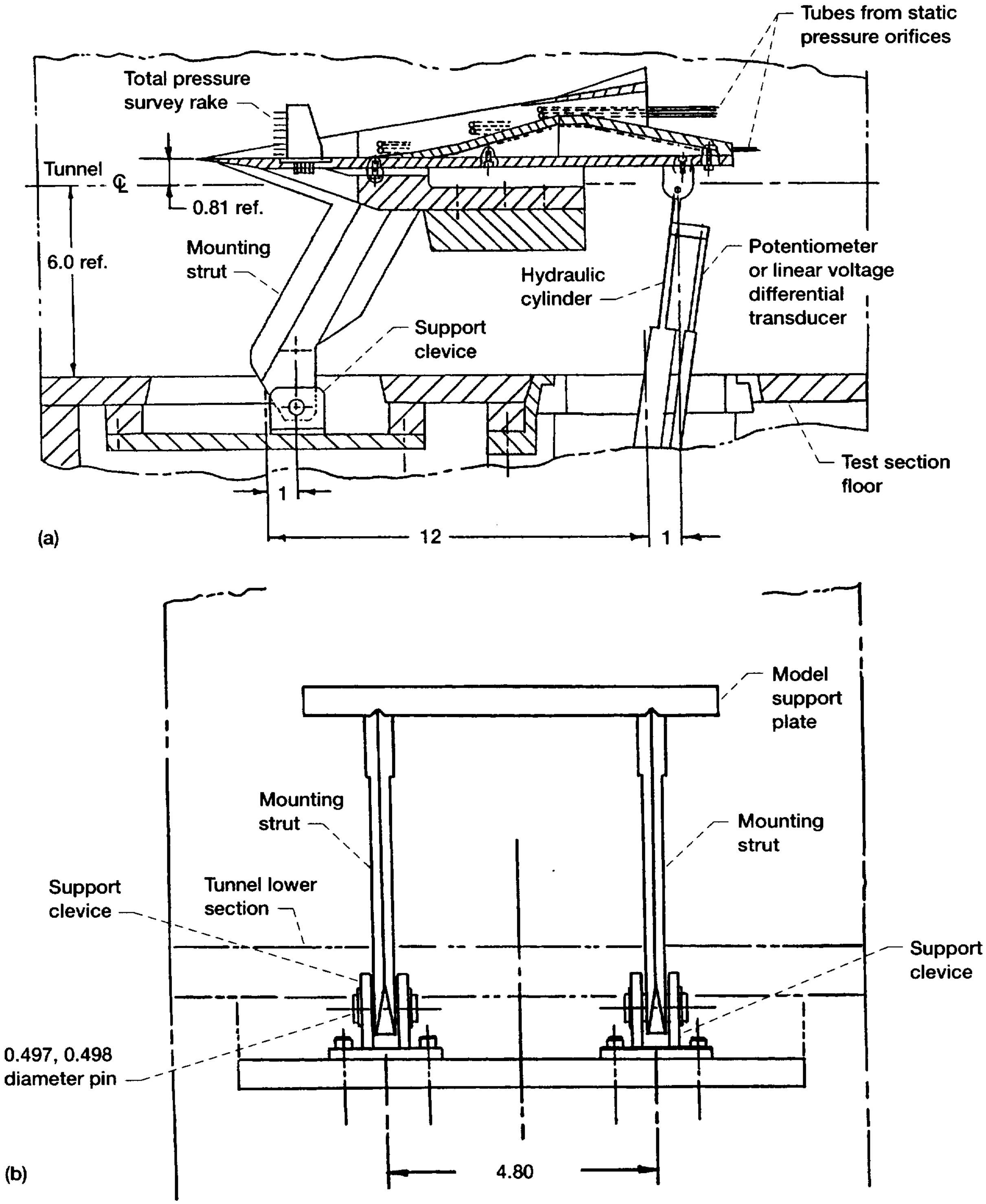
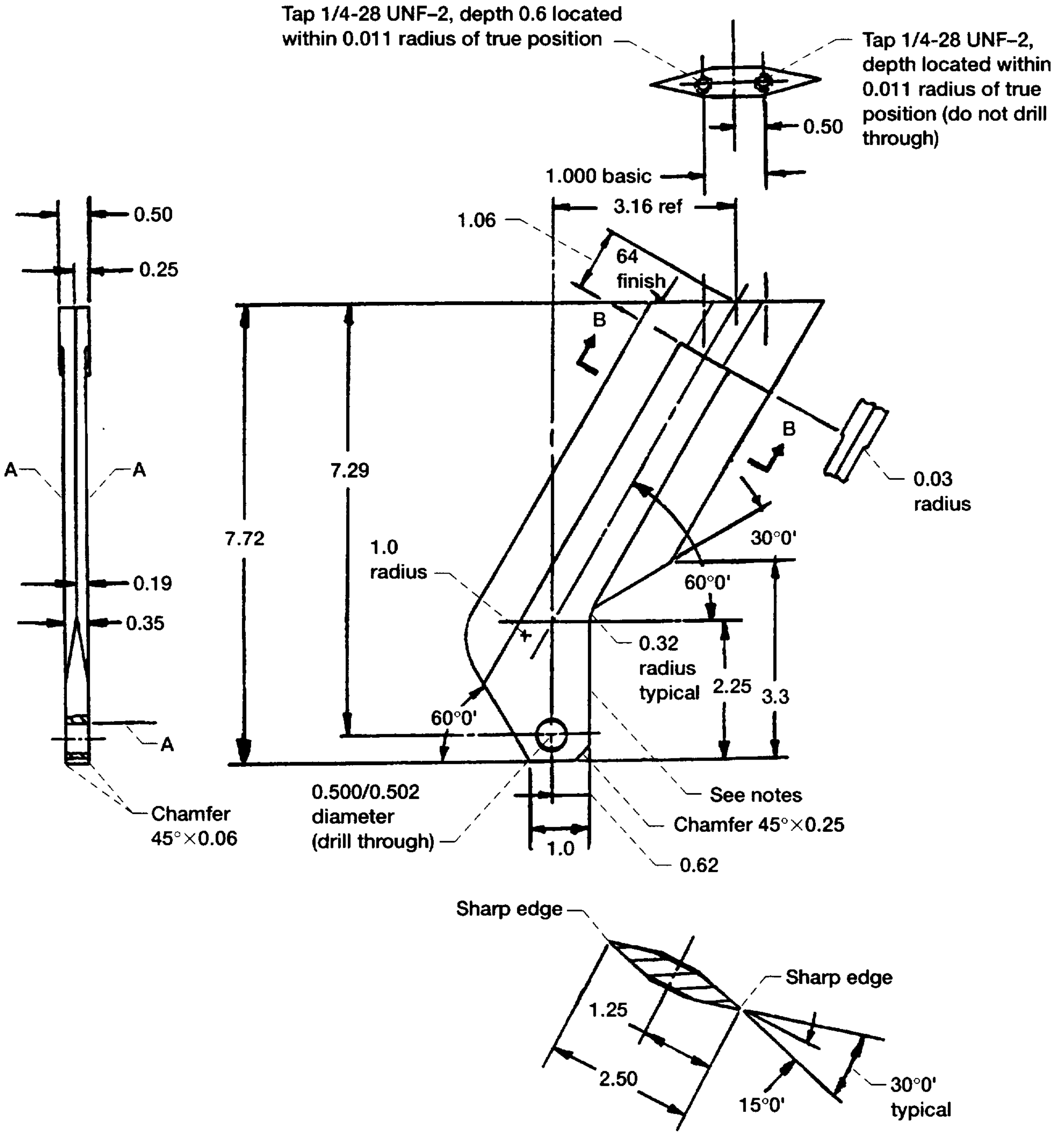


Figure 19.—Typical model mounting system. All dimensions are in inches. (See ref. dwg. CF 644888, available from the project engineer.) (a) Elevation view. (b) Plan view.



SPECIFICATIONS

Surfaces	Must be concentric, parallel, flat, square and true (as applicable) to each other within 0.005 full indicator reading
Material	SAE 1010–1030 steel or SAE 11617 steel (Society of Automotive Engineers) optional
Finish	125 finish all over except where noted otherwise; black oxide per AMS 2485 (American Metals Society)

Figure 20.—Model mounting strut. All dimensions are in inches unless marked otherwise.

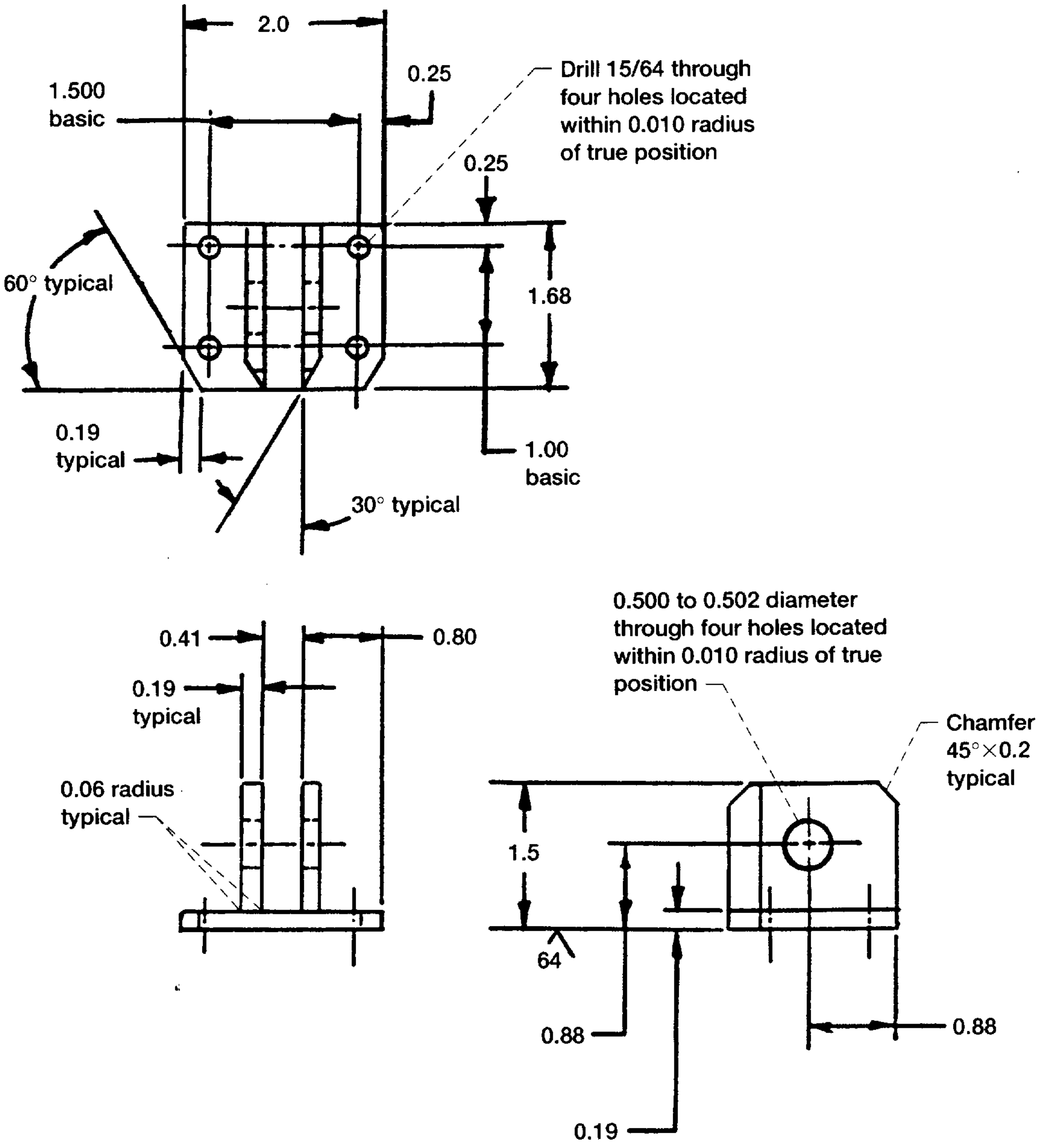


Figure 21.—Support clevice. All dimensions are in inches unless marked otherwise.

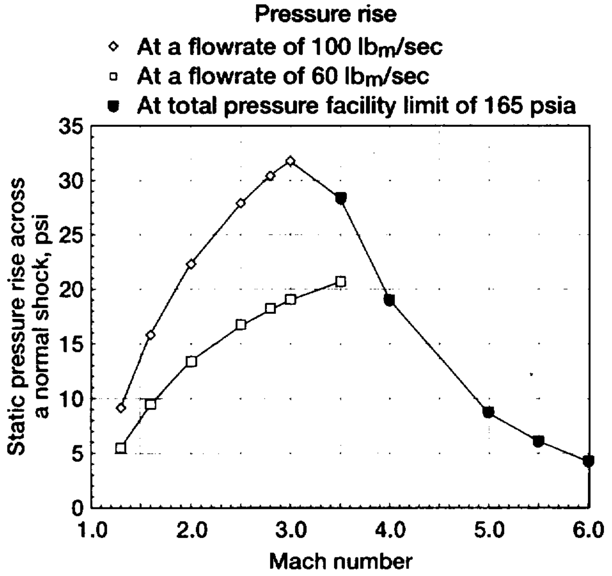


Figure 22.—Static pressure rise across a normal shock as a function of Mach number.

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11. SUPPLEMENTARY NOTES

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13. ABSTRACT *(Maximum 200 words)*

This manual describes the NASA Glenn Research Center's 1- by 1-Foot Supersonic Wind Tunnel and provides information for customers who wish to conduct experiments in this facility. Tunnel performance envelopes of total pressure, total temperature, and dynamic pressure as a function of test section Mach number are presented. For each Mach number, maps are presented of Reynolds number per foot as a function of the total air temperature at the test section inlet for constant total air pressure at the inlet. General support systems—such as the service air, combustion air, altitude exhaust system, auxiliary bleed system, model hydraulic system, schlieren system, model pressure-sensitive paint, and laser sheet system—are discussed. In addition, instrumentation and data processing acquisition systems are described, pretest meeting formats and schedules are outlined, and customer responsibilities and personnel safety are addressed.

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