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THE LANGLEY THERMAL PROTECTION SYSTEM TEST FACILITY: A DESCRIPTION INCLUDING DESIGN OPERATING BOUNDARIES

(NASA-TM-X-73973) THE LANGLEY THERMAL PROTECTION SYSTEM TEST FACILITY: A DESCRIPTION INCLUDING DESIGN OPERATING BOUNDARIES (NASA) 31 p HC A03/MF A01 CSCL 14B G3/09

N77-11067

Unclas

54509

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November 1976

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THE LANGLEY THERMAL PROTECTION SYSTEM TEST FACILITY: A DESCRIPTION INCLUDING DESIGN OPERATING BOUNDARIES

by George F. Klich

Langley Research Center

SUMMARY

A description of the Langley Thermal Protection System Test Facility is presented. This facility was designed to provide realistic environments and times for testing thermal protection systems proposed for use on high-speed vehicles such as the space shuttle. Products from the combustion of methane-air-oxygen mixtures, having a maximum total enthalpy of 10.3 MJ/kg, are used as a test medium. Test panels with maximum dimensions of 61 cm x 91.4 cm are mounted in the side wall of the test region. Static pressures in the test region can range from .005 to .1 atm and calculated equilibrium temperatures of test panels range from 700 K to 1700 K. Test times can be as long as 1800 sec.

Some experimental data obtained while using combustion products of methane-air mixtures are compared with theory, and calibration of the facility is being continued to verify calculated values of parameters which are within the design operating boundaries.

INTRODUCTION

The design of reusable, high-speed flight vehicles such as the space shuttle is governed by requirements such as protection from extreme heating loads, low structural weight, and the capability for providing a large number of successful missions. The loads due to aerodynamic heating can result in deformation and erosion of vehicle external surfaces which serve as thermal protection systems for basic structures. Consequently, design activities will include evaluations of new and untried materials as well as minimization of material thicknesses.

Since vehicle surfaces which are in contact with the stream may deform or erode in an unpredictable manner, because of non-uniform heating over a long period of time, realistic tests are required to assure full knowledge of the material behavior and performance. Actual flight testing is generally not feasible, and most existing test facilities have limitations which prevent realistic duplication of flight time periods and temperatures. To alleviate this situation, the Langley Thermal Protection System Test Facility (TPSTF) has been designed and constructed. This facility provides the capability for aerodynamically heating full-scale thermal protection systems (which include support structures, insulation, heat shields, etc.) to the correct surface temperatures and maintaining those temperatures for time periods as long as 1800 sec. This report presents a description of this new facility, which currently is in the shakedown and calibration phase of operation.

SYMBOLS

H	enthalpy, J/kg
P	pressure, atm (1 atm = 101.3 kPa)
T	temperature, K
q	heat flux, W/m^2
ε	emissivity
τ	shear force, Pa

Subscripts:

T	total
N	nozzle
w	wall

DESCRIPTION OF THE TPSTF

General

The TPSTF is a blowdown wind tunnel with a plenum chamber in which combustion processes are used for energy conversion. The various components of the facility are identified in figure 1. Methane is burned with air and/or oxygen in the combustion chamber at pressures ranging from 2 to 20 atmospheres. The combustion process raises the temperatures of the gases to 3450 K at a maximum enthalpy of 10.3 MJ/kg; the resulting products are expanded through a 2-dimensional nozzle to supersonic velocities in the test region, then flow through a diffuser system and an exhaust stack to the atmosphere. A single stage annular air ejector permits starting and operating the tunnel at combustor pressures of less than 10 atm.

Components of the tunnel upstream of the ejector are water cooled in order to maintain internal surface temperatures at a safe level. At combustor pressures greater than 10 atm air from the ejector is used as a diluent for the combustion gases and to prevent overheating of the mixing tube, subsonic diffuser and exhaust stack. Test panels are installed flush in the test section wall, as indicated in figure 1 and described in a subsequent section of this report.

Fuel and air for the combustor and ejector are obtained from on-site supplies at the Thermal Structures Branch complex, a photograph of which is shown in figure 2. The volume of the fuel storage bottles is 68 m^3 and the air storage field has a volume of 374 m^3. These gases are stored at pressures up to a maximum of 408 atm. Oxygen is stored as a liquid, vaporized, and pumped into 5 tube trailers (total volume of 108 m^3) at pressures up to 163 atm for use as a reactant in the combustor. Test run duration is usually limited by the oxygen supply, since the minimum oxygen storage pressure required to operate the facility is 82 atm. Nitrogen, which is also stored on-site, is used as a purge gas for the fuel and oxygen systems.

Combustor

A photograph of the combustor, a sudden expansion burner, is presented in figure 3. It is essentially a pressure vessel containing an interference fitted circular bundle of tubes. Relatively thin-wall tubes are welded together to form a 35.5-cm-diameter combustion chamber. The tubes also serve as longitudinal cooling water passages. To establish a flame, air is introduced through a 10.2-cm-diameter pipe at the upstream end of the combustor. The sudden enlargement of the flow area at the entrance to the combustor, as indicated in figure 4, promotes mixing of the air with the fuel which is injected into the recirculation zone through 8 tubes at the upstream end of the combustor. Initially, a spark plug is used to ignite a hydrogen-air mixture, which subsequently ignites the methane-air mixture. After the flame is established, oxygen is either pre-mixed with or completely replaces air for the combustion process.

Subsonic Transition Sections

Conversion from the circular combustor to the two-dimensional geometry of the nozzle is accomplished through two transition sections as shown in figure 5. Transformation from the 35.5 cm diameter to a 30.5 cm x 35.5 cm rectangle is made in one section which is 22.9 cm long. The top and bottom of the downstream section diverge to the 30.5 cm x 91.4 cm dimension over a 1.37 m length. Initially, the angle of divergence is 10° with a change to 14° about midway of the length of the section. These angles were selected to prevent flow separation and the consequent high heat fluxes of reattachment. Cooling water at a pressure of 27.2 atm flows through passages that were formed by brazing a thin skin to lands, which remained after grooves were milled in the inner face of the structural members. In addition, the inner metallic surfaces of the downstream section are coated with an 0.635 mm thick layer of flame-sprayed nickel aluminide and zirconium oxide to reduce temperature gradients in the metal skin.

The ceramic coating consists of four sub-layers; three layers, each 0.0762 mm thick, contain, respectively, 100 percent, 67 percent, and 33 percent nickel aluminide. The layer exposed to the stream is about 0.33 mm thick and is composed of 100 percent zirconium oxide.

Nozzle

The supersonic nozzle is contoured with throat dimensions of 1.22 cm x 91.4 cm and exit dimensions of 30.5 cm x 91.4 cm. Contours were determined for inviscid flow of methane-air-oxygen combustion products having a total enthalpy of 5.35 MJ/kg. No corrections were made for displacement thicknesses, however, due to uncertainties in the effects of very thick boundary layers and the rather large operating range. The design Mach number is nominally 3.7, but the Mach numbers actually obtained in the test section over the operating range will be determined experimentally. The nozzle is in two sections: the nozzle throat and the nozzle extension. The throat region is designed to accommodate the associated high heat fluxes by varying the skin thicknesses and through the use of cooling water pumped at a pressure of 34 atm through contoured passages, as shown in figure 6. The supersonic portion of the nozzle, where the heat fluxes are relatively low, is cooled by water at 10.2 atm.

Test Medium

Mass fractions of the combustion reactants for the range of operation are shown in figure 7. It should be noted that for a major portion of the operating range the oxygen content of the combustion products is similar to that of air. Other major constituents of the combustion products are H_2O, CO_2, CO, OH, with N_2 and NO at the lower temperatures. No condensation of the H_2O vapor is expected since the static temperatures are relatively high; however, the high temperatures will promote dissociation of the molecular gases. When operating at or near the stoichiometric mixture, it is expected that expansions through the nozzle will result in some frozen flow. The effects of non-equilibrium in the test medium and the catalycity of various surfaces will be determined during the calibration tests of the facility.

Test Section

The test region of the tunnel is a closed test section with cross-section measurements of 30.5 cm x 91.4 cm and a length of approximately 1.22 m. Panels measuring up to 61 cm x 91.4 cm can be installed in the side of the test section.

A photograph of a test panel holder is shown in figure 8 and a photograph of a calibration panel mounted in the holder is shown in figure 9. This panel is a water cooled structure containing two retractable stream probes, which can be extended to a maximum distance of 15.2 cm into the stream, for measuring stagnation point heat fluxes and pitot pressures. Static pressure orifices and cold-wall heat flux gauges are installed in the surface of the panel as indicated in figure 10. The number of units of each type of instrument installed

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in the panel is shown in parentheses.

A holder, which will protect fragile research models during the start-up and shutdown loads imposed on the test section, is being fabricated. A conceptual sketch of the protective panel holder is shown in figure 11. A sliding door covers and protects panels from the transient loads; vents in the door allow the pressure around the panel to equalize gradually with the test section pressure before the door is removed and the test panel positioned in the side of the test section.

The opposite side of the test section is a solid, water-cooled structural panel, which can be removed to provide access to the test panel for inspection and repair. This water-cooled panel can also be replaced with another panel containing six 15.2 cm diameter, air film-cooled quartz windows. The windows are spaced as indicated in figure 12 to provide views that will include the entire surface of the test panel.

Diffusers and Ejector

Deceleration of the flow is accomplished in a supersonic diffuser 3.3 m long, as shown in figure 1. The shock wave system is initiated by the upper and lower walls of the section, which converge at an angle of 7.5° for a length of 0.86 m where internal measurements are 0.31 m x 0.69 m. The geometry of the diffuser then changes to circular cross-section with a terminal portion 0.76 m long having a constant diameter of 0.51 m. The flow is discharged to the mixing tube of the single stage air ejector, which is used for starting and operating the tunnel. The ejector mixing tube is about 8 diameters long and terminates in a 4 degree half angle subsonic diffuser. The supersonic diffuser and ejector nozzle are water cooled. Normally the ejector nozzle pressure required to start the tunnel is about 23.8 atm. The pressure requirements of the ejector needed to maintain supersonic flow decrease as the tunnel operating pressure increases; however, air from the ejector is also used as a coolant for the mixing tube when necessary. The ejector controls are integrated with the tunnel safety interlock system, so that the control valve will go to its full open position to clear the tunnel of any hazardous gas mixture in the event of electric or hydraulic power loss or if fuel is detected in the test panel holder or the test cell.

Exhaust Stack

Effluents from the tunnel are exhausted to the atmosphere from a vertical, uncooled metal stack which is 1.82 m in diameter and 4.57 m high. Discharge velocities of the tunnel products are reduced to about 15.2 m/sec with a maximum temperature of 1390 K. Calculations indicate temperatures in the exhaust tube and the residence time of the gases are sufficient for atmospheric pollutants to react and adjust to acceptable levels.

Cooling Water System

Water for cooling tunnel components is obtained from a tower by a 93.2 kJ/s pump at a pressure of about 4.75 atm. The maximum capacity of this pump is 0.328 m^3/s. The water is distributed to the various tunnel components by three high pressure pumps. A 27.4 atm pump supplies 0.033 m^3/s to the combustor and 0.04 m^3/s to the transition sections. A 34.atm pump supplies .076 m^3/s to the nozzle throat section. The remaining water-cooled components are supplied by a 10.2 atm pump. The total amount of water used for cooling purposes is about 0.208 m^3/s.

Tunnel Controls

Figure 13 is a photograph of the TPSTF control panel. The main tunnel controls are four independent, closed loop, electro-hydraulic servo systems. Three of these control the air, fuel, and oxygen flows to the combustor. These systems are being further automated with a computer system, so that heating rate and pressure histories of desired trajectories may be easily duplicated. The fourth servo system is used to control the pressure at the ejector nozzle. Although the control system for each gas is independent of the others, all are integrated with the tunnel safety interlock system. The fuel control valve is operative only after the proper cooling-water flow rates through the tunnel components have been established, the combustor has been pressurized, and the ejector has reduced the pressure in the test region to the proper level. The valve fails-safe in a closed position if ignition is not obtained within a preset time or if an established flame is extinguished. In addition to the restraints on the fuel system, the oxygen control valve is operative only during the time when a flame exists in the combustor. This valve also fails-safe in a closed position if an established flame is extinguished.

In order to reduce starting loads and eliminate the possibility of combustible mixtures accumulating in the tunnel, the igniter system is activated at the minimum combustor pressure that will insure supersonic flow in the test section.

Data Acquisition

There are 146 instrumentation cables for data from the tunnel or test panels. Forty-eight of these contain two wires for thermocouples and 98 cables contain four wires for strain gauges. Provisions exist for recording data on various types of equipment which will accommodate a large range of frequency requirements. A common time system provides for time correlation among the different data recording systems.

Provisions are being made for recording test panel surface temperatures through the use of an infrared scanning system. This system will record temperatures up to 2400 K and will either generate thermographic pictures of an area 16 times per second or furnish a line scan 1600 times a second. Pictures can either be black and white with shades of gray corresponding to temperatures

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intermediate to selected extremes or 10 colors may be assigned to represent temperatures in a selected range. Data can also be recorded on magnetic tape which can be replayed, edited, and digitized.

DESIGN OPERATING CONDITIONS

The design operating boundaries for the facility, in terms of equilibrium temperatures and surface pressures of a test panel are indicated on figure 14. More recent calculations indicate that some non-equilibrium chemistry will exist during the expansion of gases having an enthalpy greater than about 6.9 MJ/kg. The presence of non-equilibrium conditions will result in some decreases in panel test equilibrium temperatures. The simulated pressure altitude ranges from 15.2 to 35.1 km. It should be noted that the limits on the operating enthalpy are based on conditions at the entrance to the nozzle, thus accounting for energy losses to the cooling water in the combustor and transition sections. Figure 15 shows the TPSTF operating envelope superimposed on a temperature-pressure history on the bottom centerline of the space shuttle at body point 1600, which is about midway of the vehicle. Times after reentry, in seconds, are noted on the curve. At the very high altitudes, temperatures can be duplicated, but panel pressures will be somewhat higher than those on the vehicle. From the time of about 550 sec to 1100 sec, temperatures and pressures expected for the space shuttle can be matched by this facility. Beyond 1100 sec, temperatures can still be duplicated, but at lower pressures than those on the vehicle.

The calculated heat flux to the surface of a test panel as a function of panel surface temperature for various tunnel operating conditions is shown in figure 16, and the calculated shear forces on a panel are indicated on figure 17.

Calculated test duration as a function of combustor pressure for the range of enthalpy at the nozzle is shown in figure 18. At low pressures, test times are limited by the large quantities of air required by the ejector to maintain supersonic flow in the test section. At combustor pressures greater than eight to ten atmospheres, the quantity of stored oxygen limits the length of test runs.

OPERATING EXPERIENCE

The facility is presently in a shakedown and calibration mode and some preliminary experimental data have been obtained with methane-air combustion products as the test medium. Figure 19 shows experimental pressure distributions compared to an isentropic expansion through the nozzle and test section. Figure 20 presents a comparison of measured cold-wall heat fluxes on the panel with theoretical results obtained from a computer program that calculates boundary layers of arbitrary gas mixtures as described in reference 1. Experimental pressures were utilized in the theoretical calculations. Average pressures were taken for points on the panel where data were scattered. Figure 21

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presents a comparison of the Mach number distribution through the boundary layer on the test panel. The experimental values were derived from pitot and static pressures measured in the test section. Pitot pressures were obtained through the use of the stream probe described previously. The static pressure was measured at the test panel surface and was assumed to be constant through the boundary layer. Some scatter in the data is expected, since it was obtained with methane-air combustion products having an enthalpy of less than 1.9 MJ/kg. That condition is outside the design operating conditions, and it is expected that data scatter will decrease as design conditions are approached.

CONCLUDING REMARKS

The Langley TPSTF is a unique facility in that combustion products of methane-air-oxygen mixtures are utilized over a large range of pressures and temperatures. The range of operating conditions and test times provides for realistic simulation of local flight conditions on high-speed vehicles, including portions of the space shuttle reentry trajectory. The facility is being operated in a shakedown and calibration mode to experimentally verify calculated values of parameters which are within the design operating boundaries.

REFERENCES

1. Grose, Ronald D., et al.: A Nonsimilar Solution for Laminar and Turbulent Boundary Layer Flows Including Entropy Layers and Transverse Curvature. Aerotherm Corporation Report No. 70-14 (Available as NASA CR-73481, 1970).

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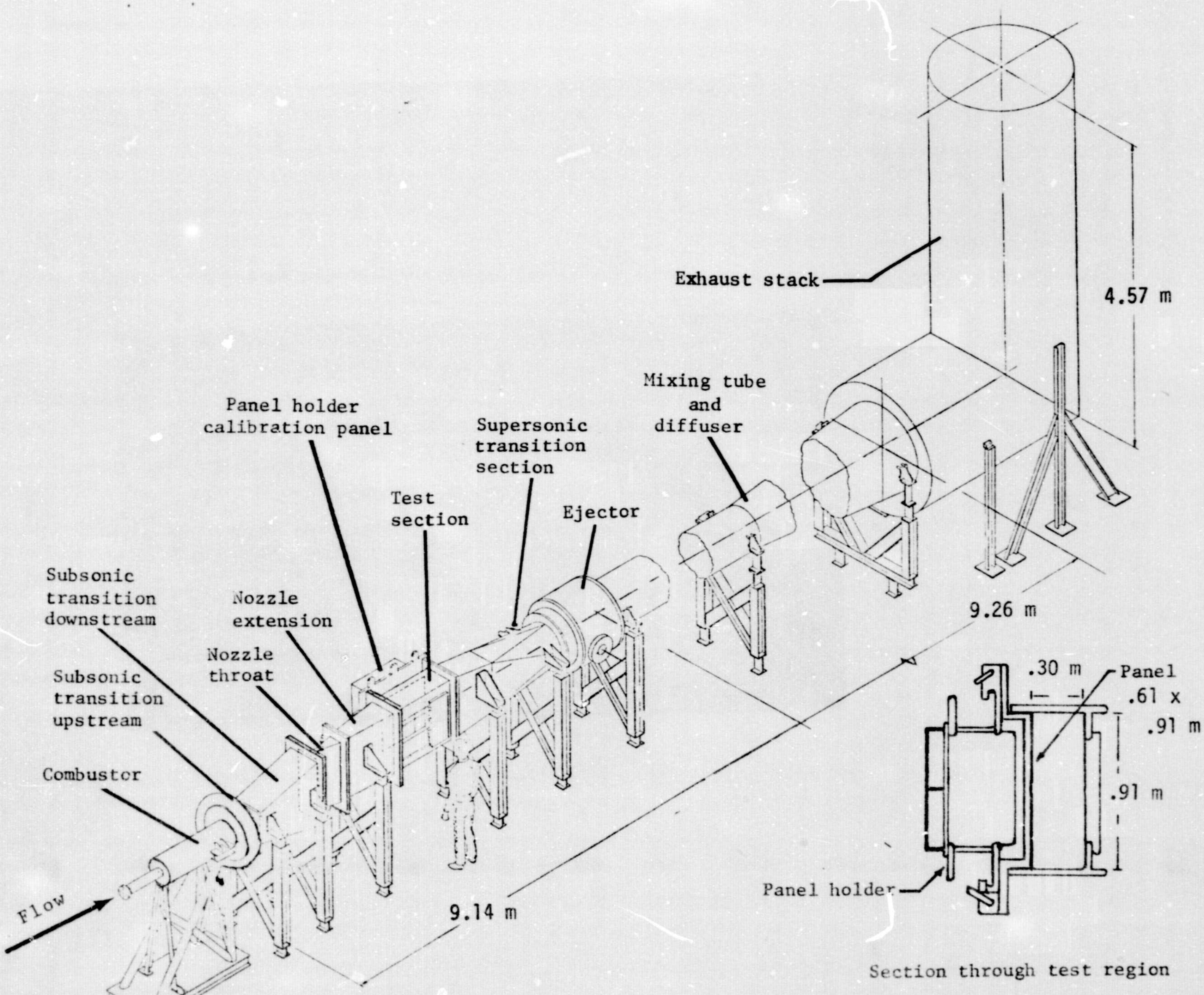

Figure 1. - Sketch showing components of the Langley Thermal Protection System Test Facility.

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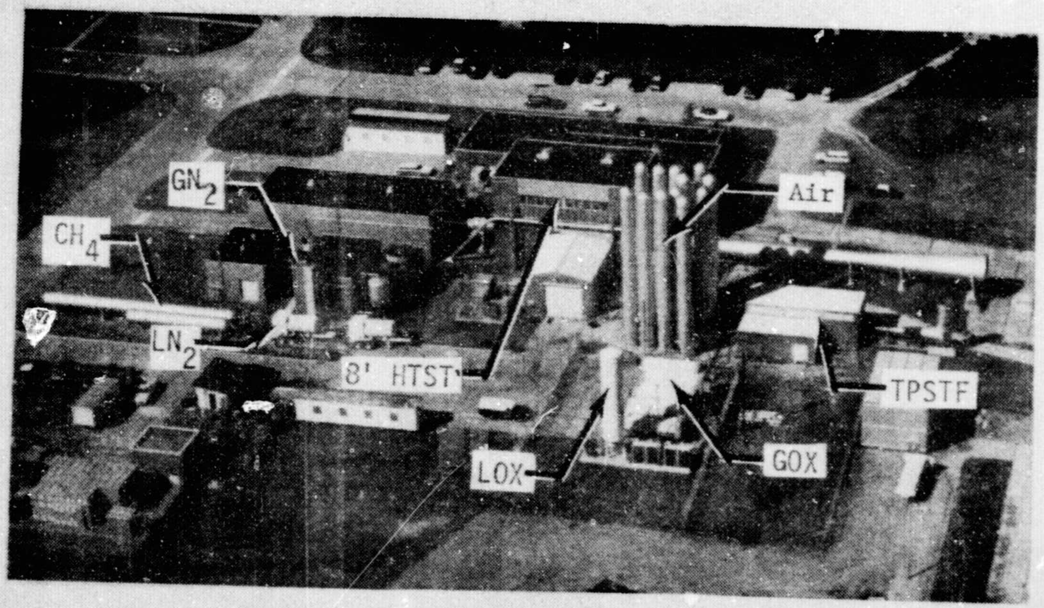

Figure 2. - Thermal Structures Branch Complex .

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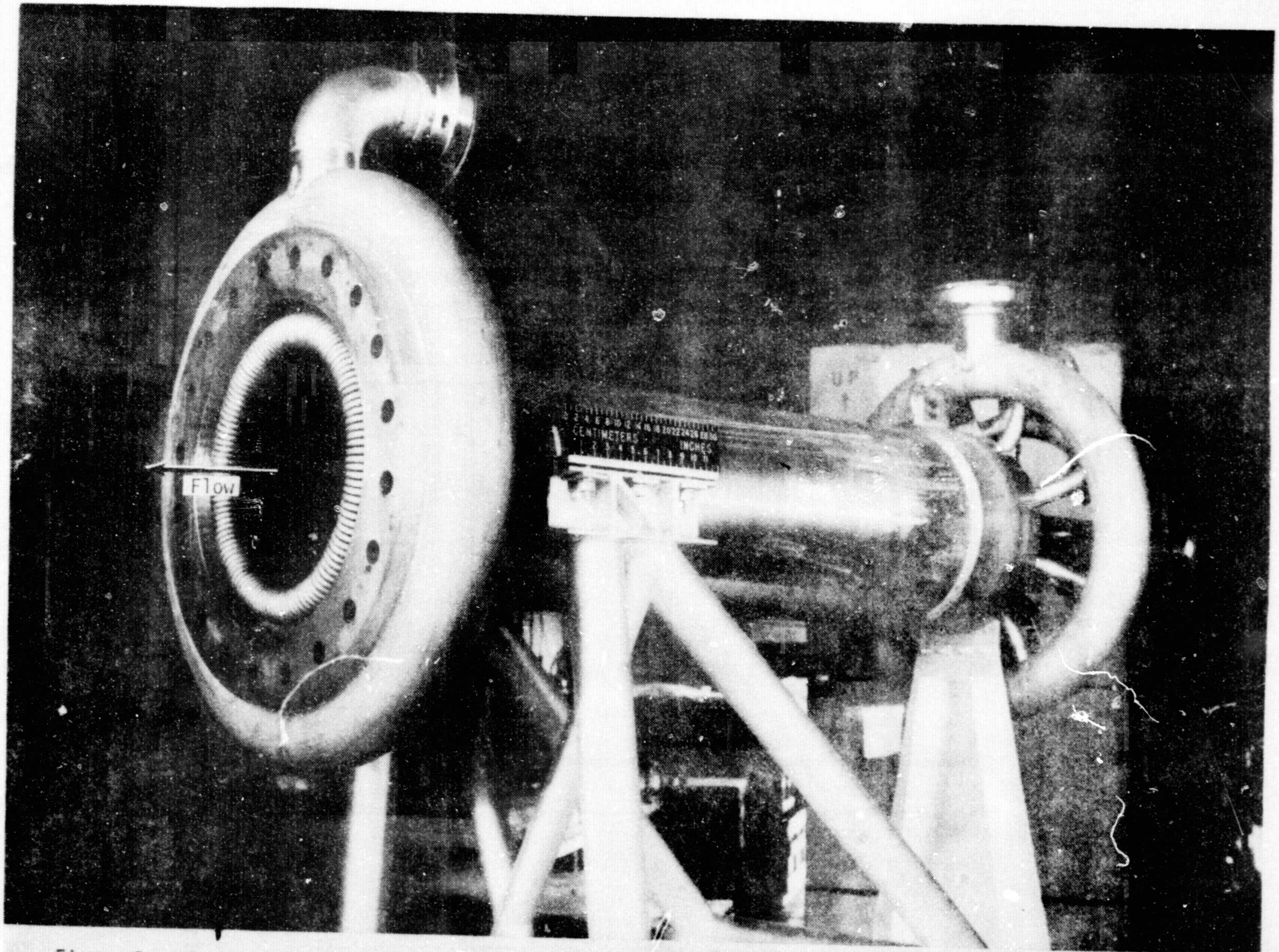

Figure 3. - Photo of TPSTF Combustor.

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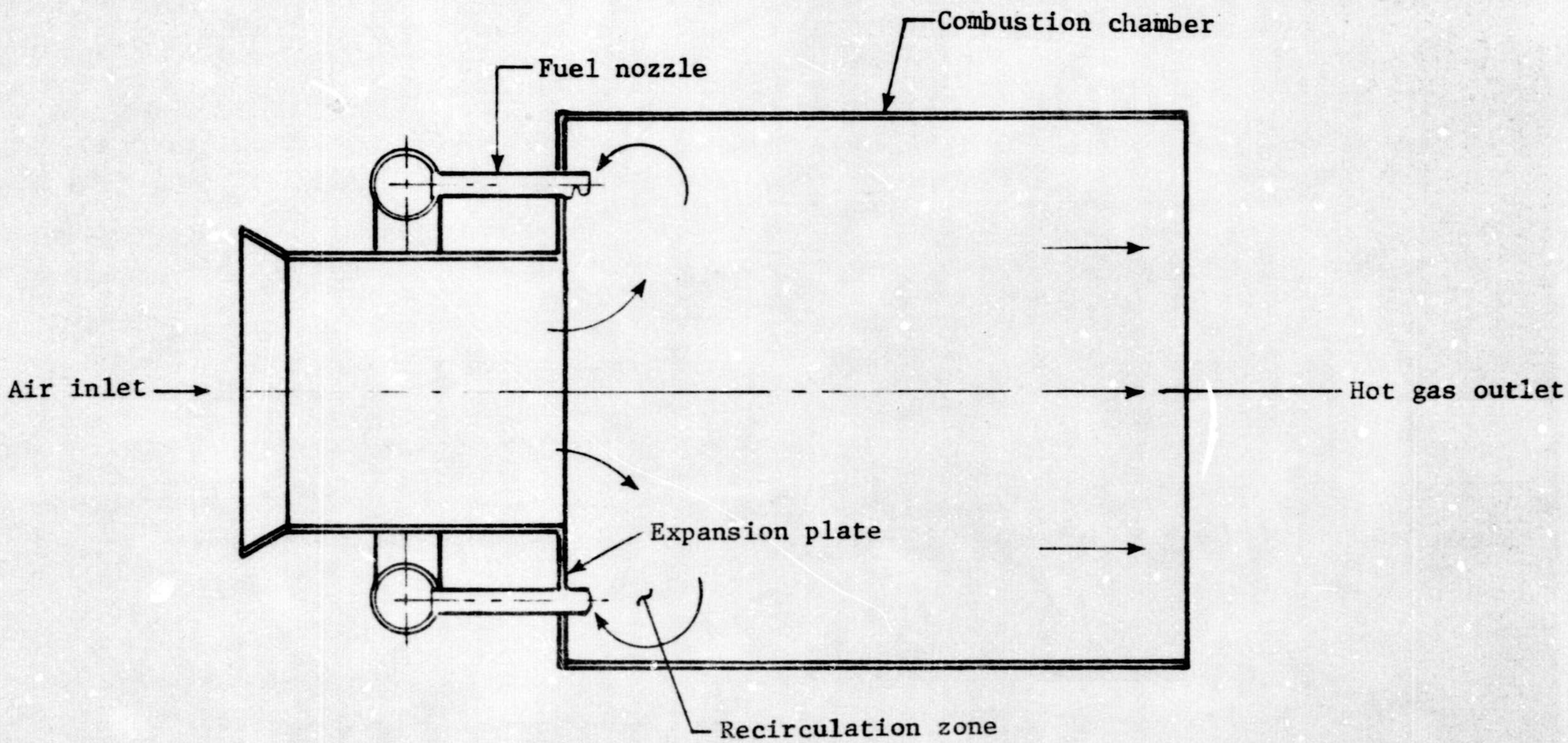

Figure 4. - Section through a typical sudden expansion burner.

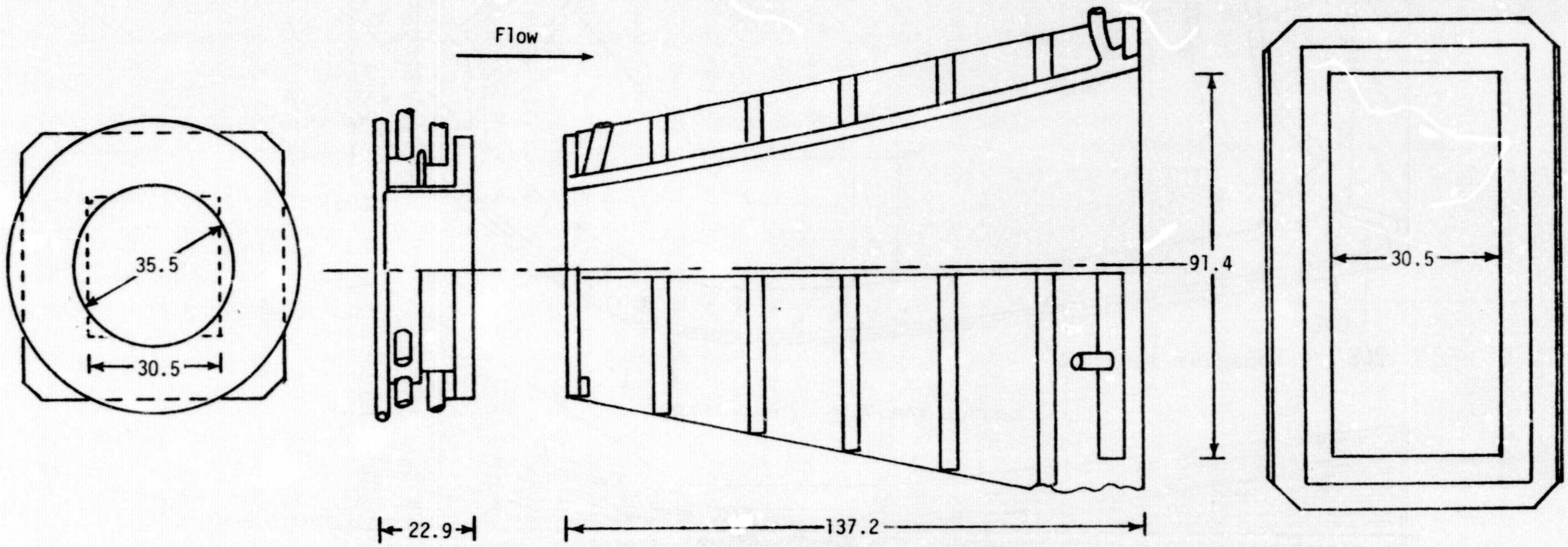

Figure 5. - Sketch of subsonic transition sections in the TPSTF.
(all dimensions are cm)

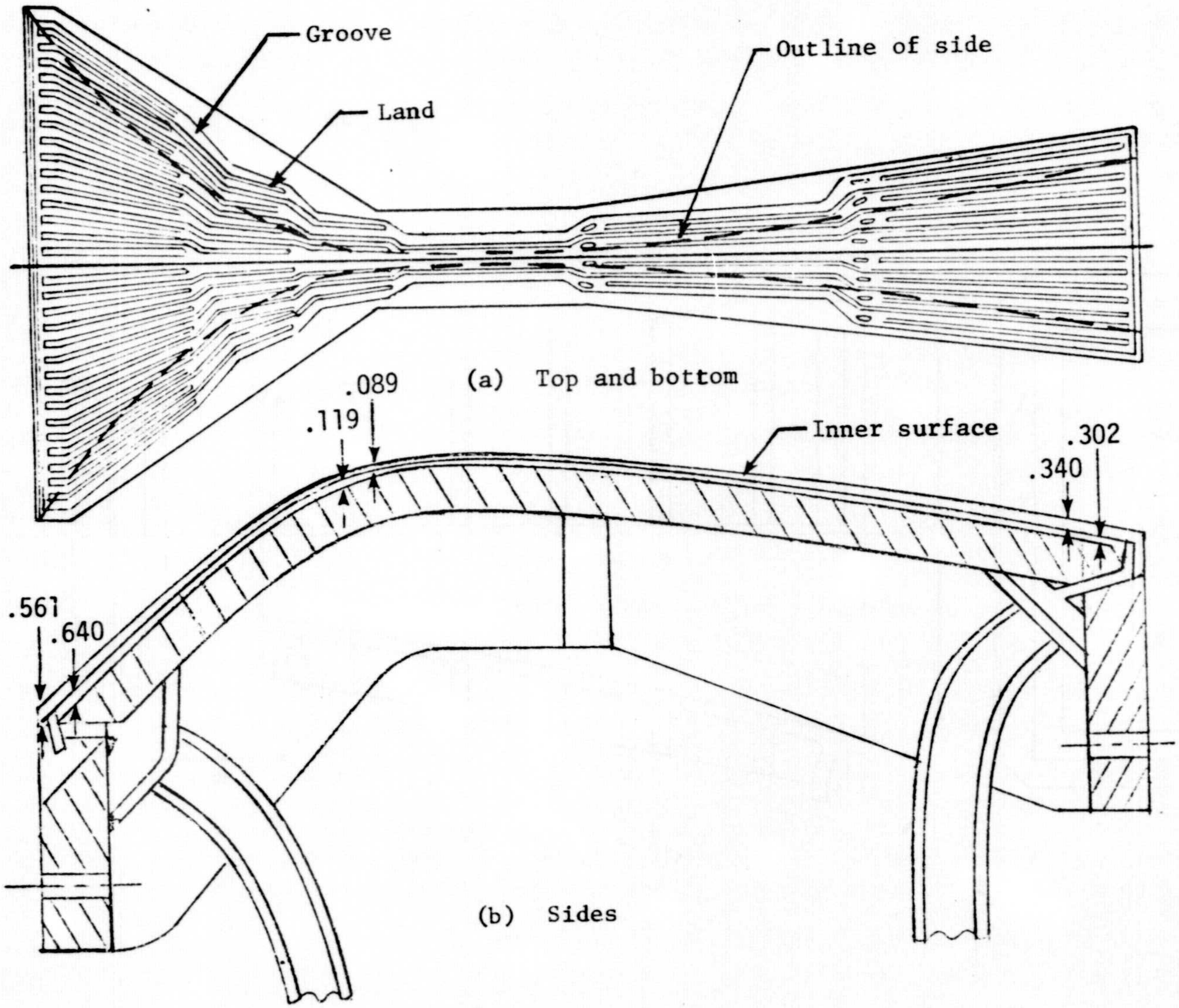

Figure 6. - Sketch of water passages and varying thickness inner skin in throat region of the TPSTF nozzle. (Dimensions, cm)

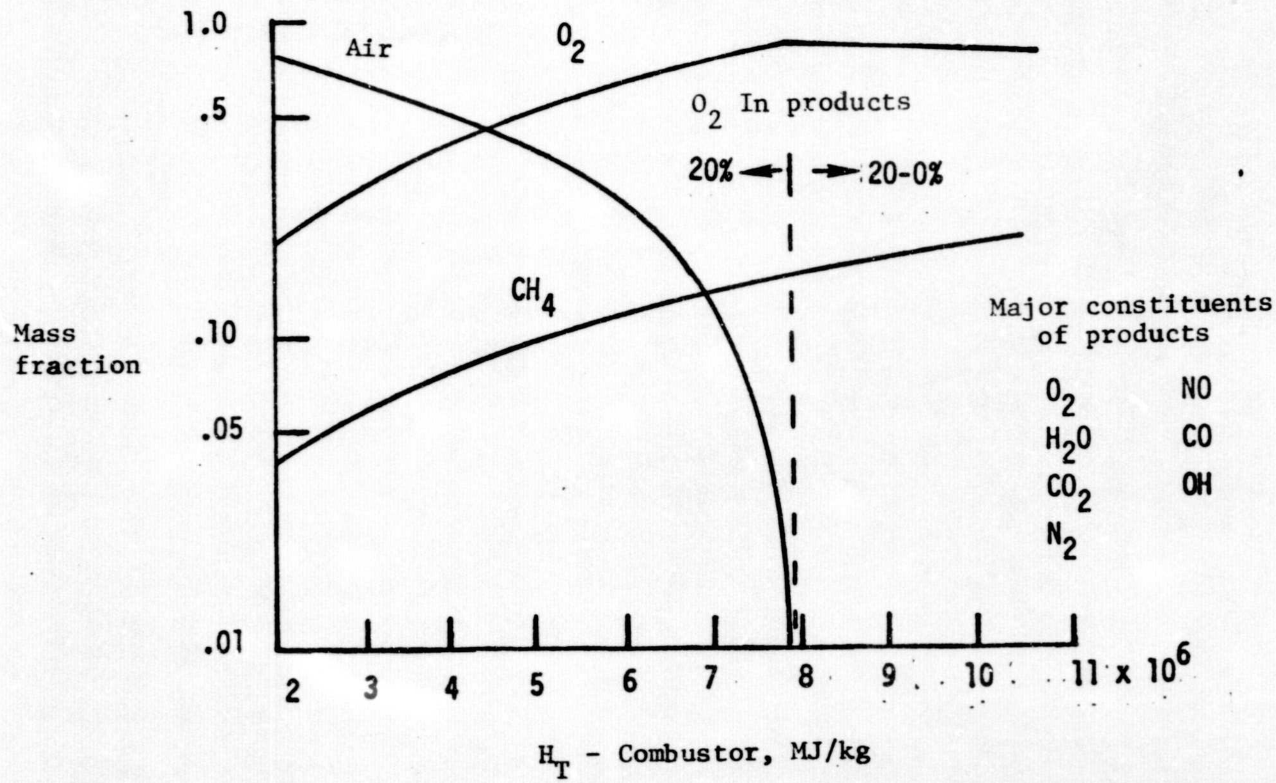

Figure 7. - Composition of TPSTF combustor reactants.

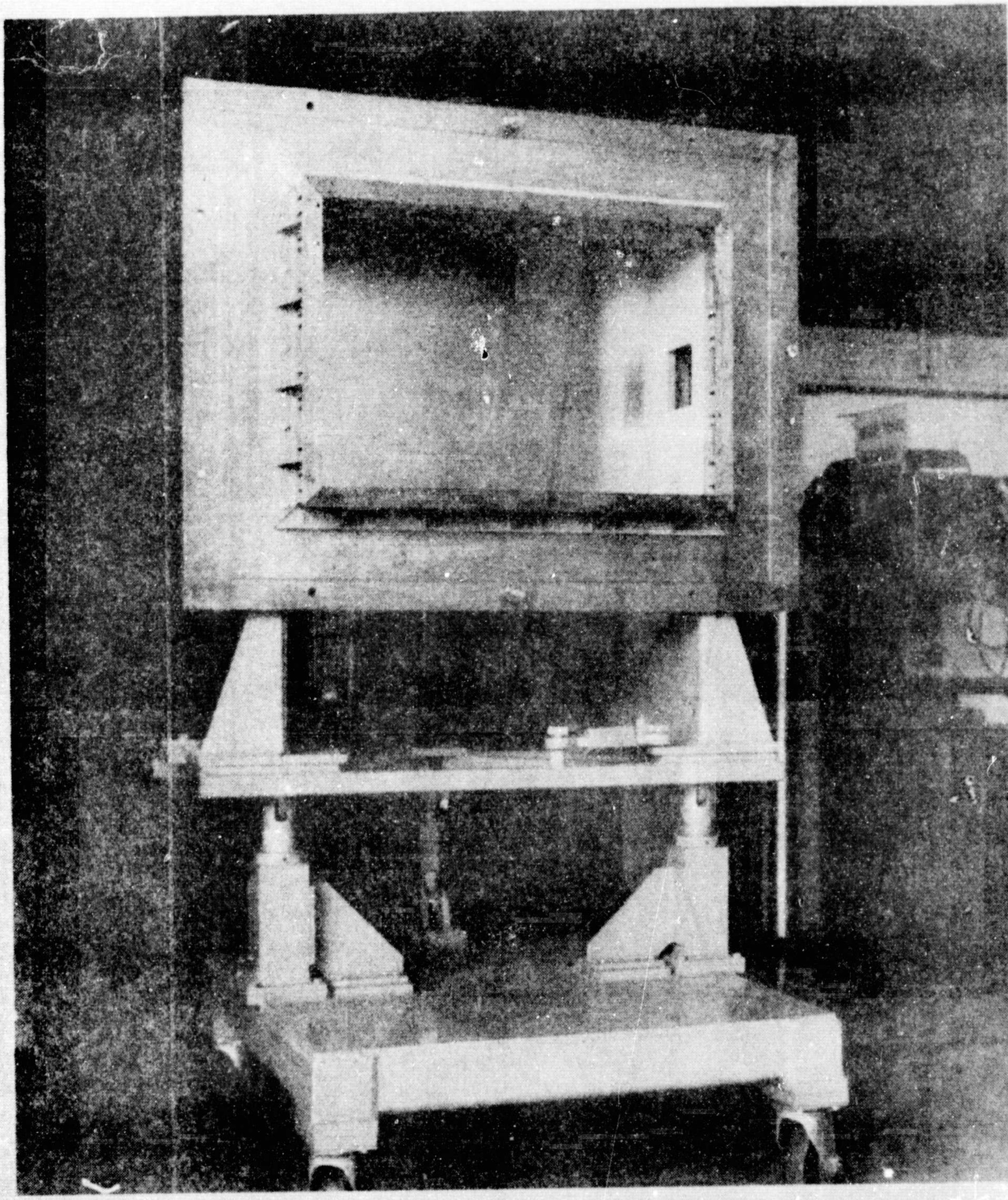

Figure 8. - Test panel holder for the TPSTF .

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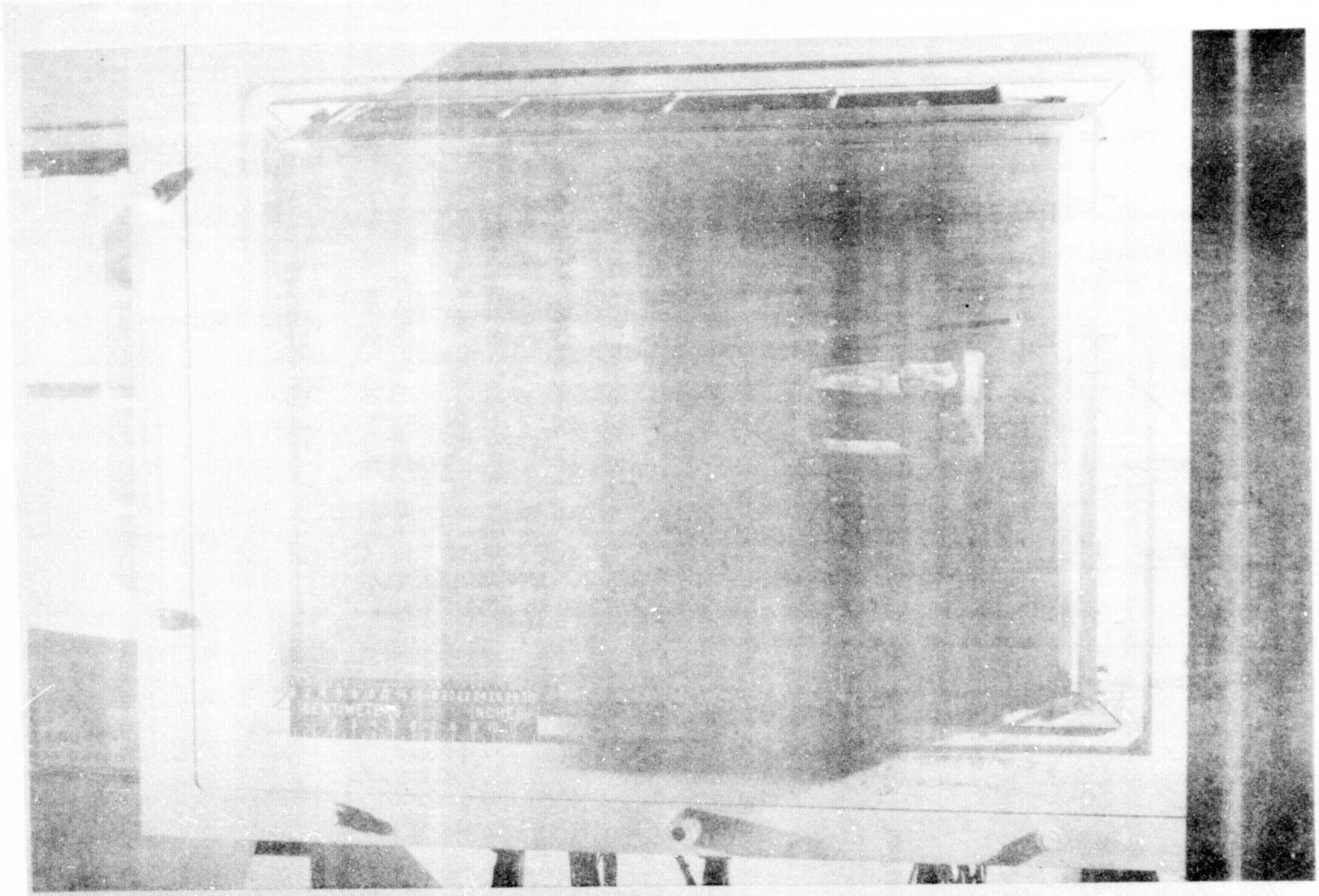
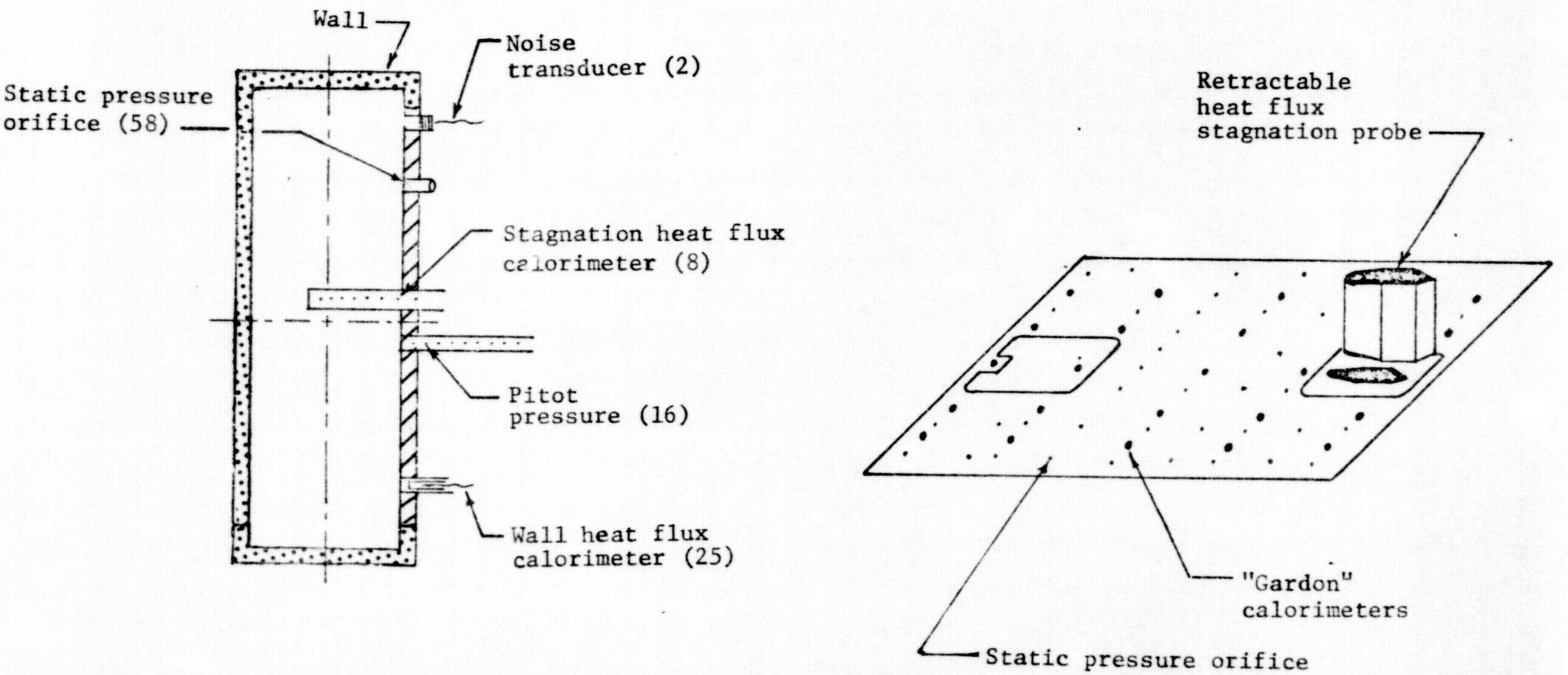


Figure 9. - TPSTF calibration panel in holder.



(a) Section thru test area

(b) Calibration panel surface

Figure 10. - Data instrumentation on TPSTF calibration panel.

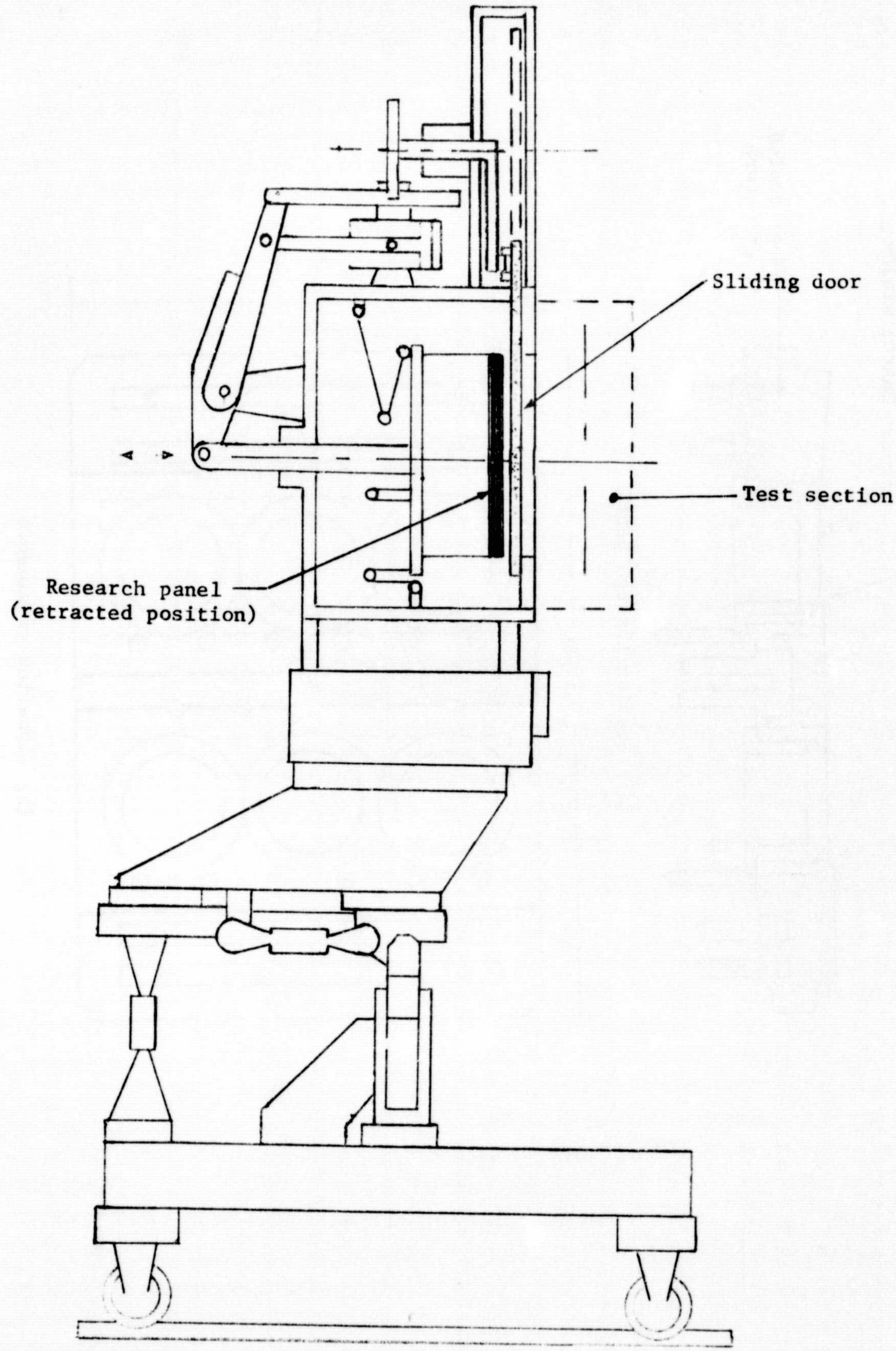
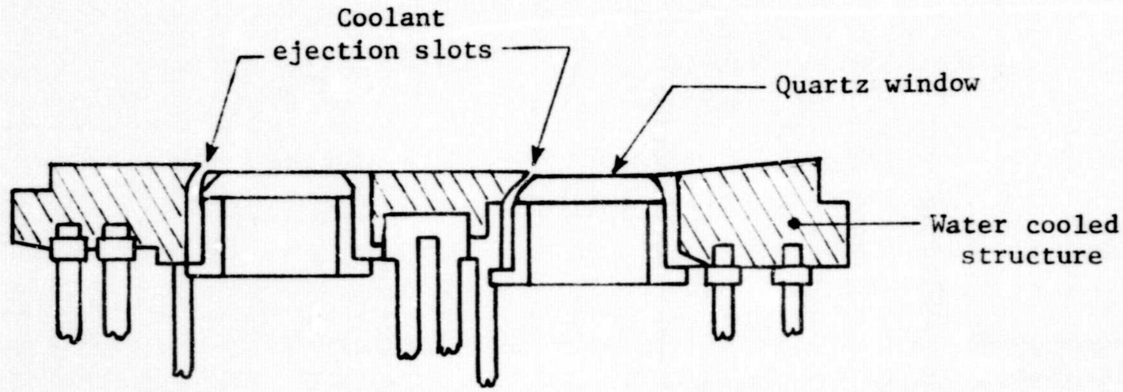
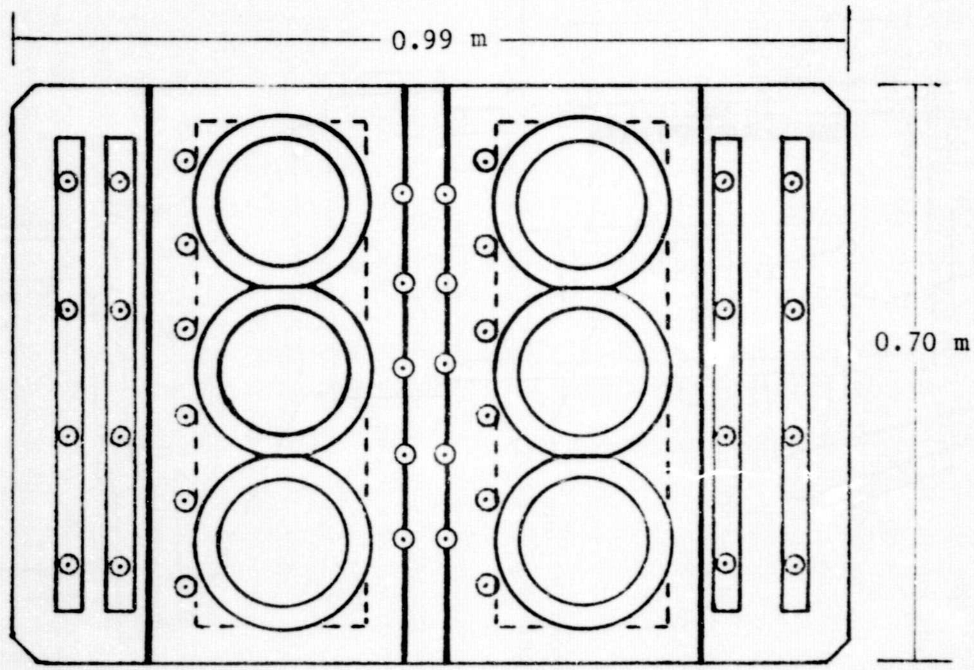


Figure 11. - Conceptual sketch of TPSTF protective panel holder.



(a) Section through panel



(b) Location of windows

Figure 12. - Sketch of window panel for the TPSTF .

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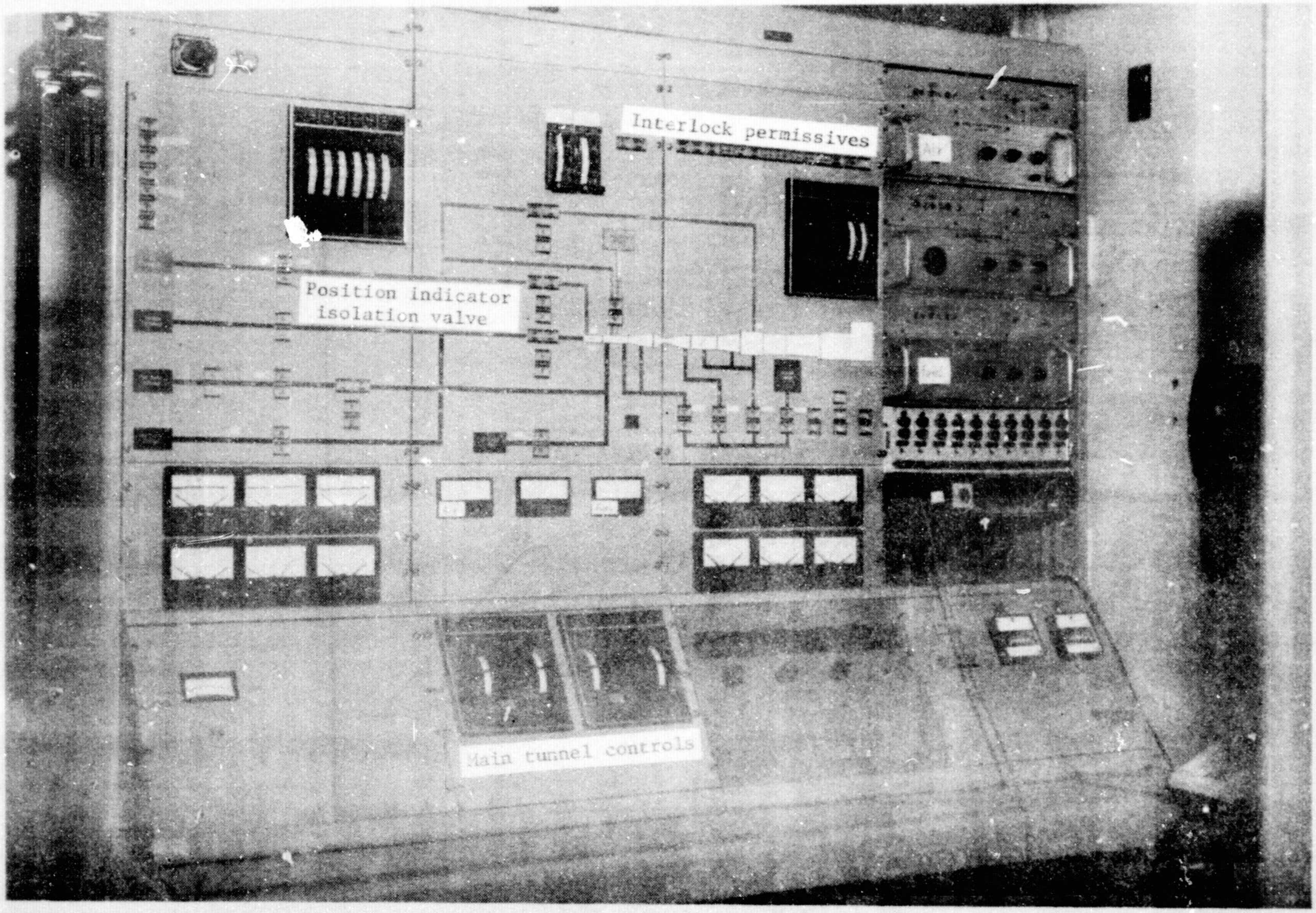


Figure 13. - TPSTF control panel.

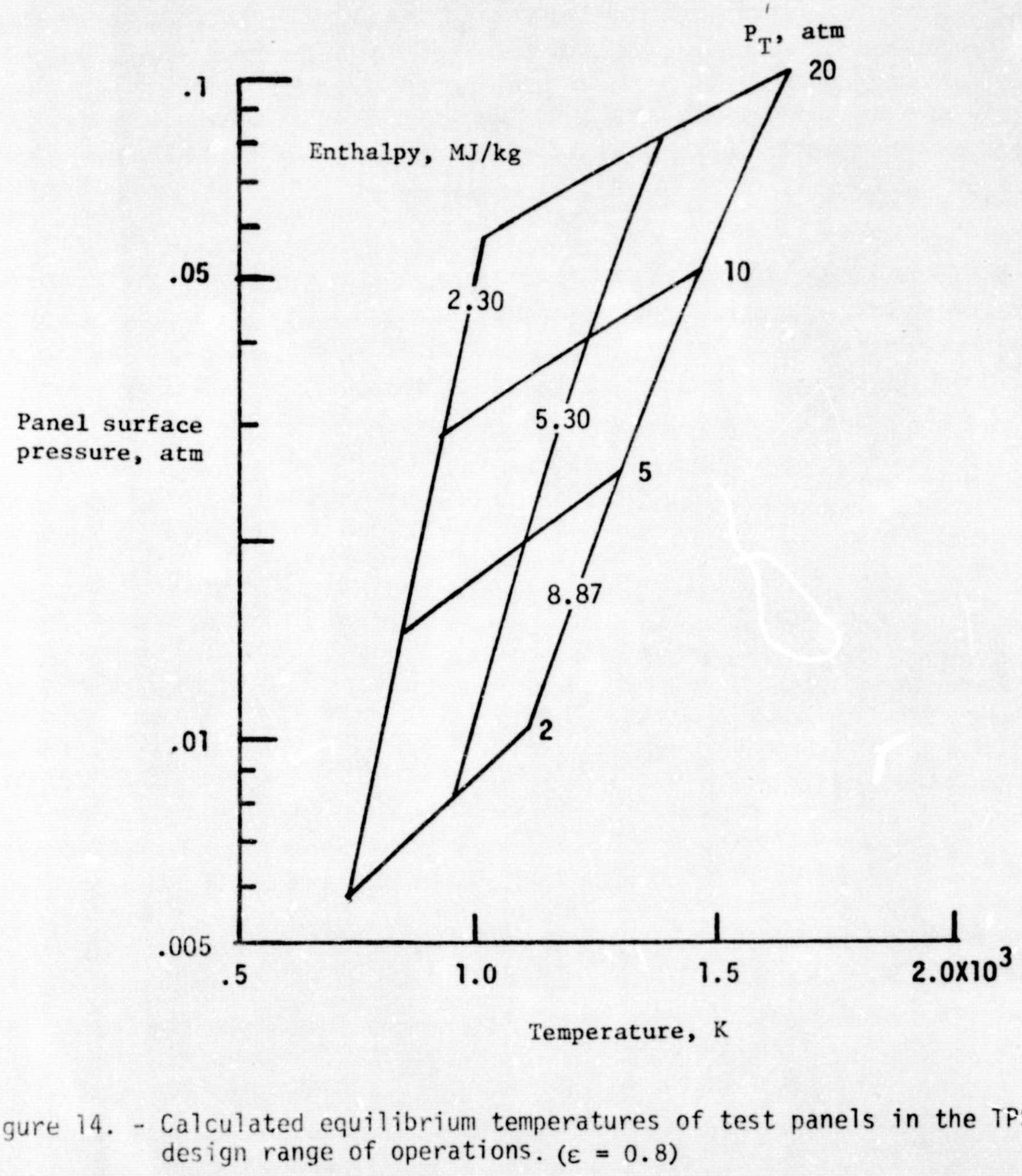


Figure 14. - Calculated equilibrium temperatures of test panels in the TPSTF for design range of operations. (ε = 0.8)

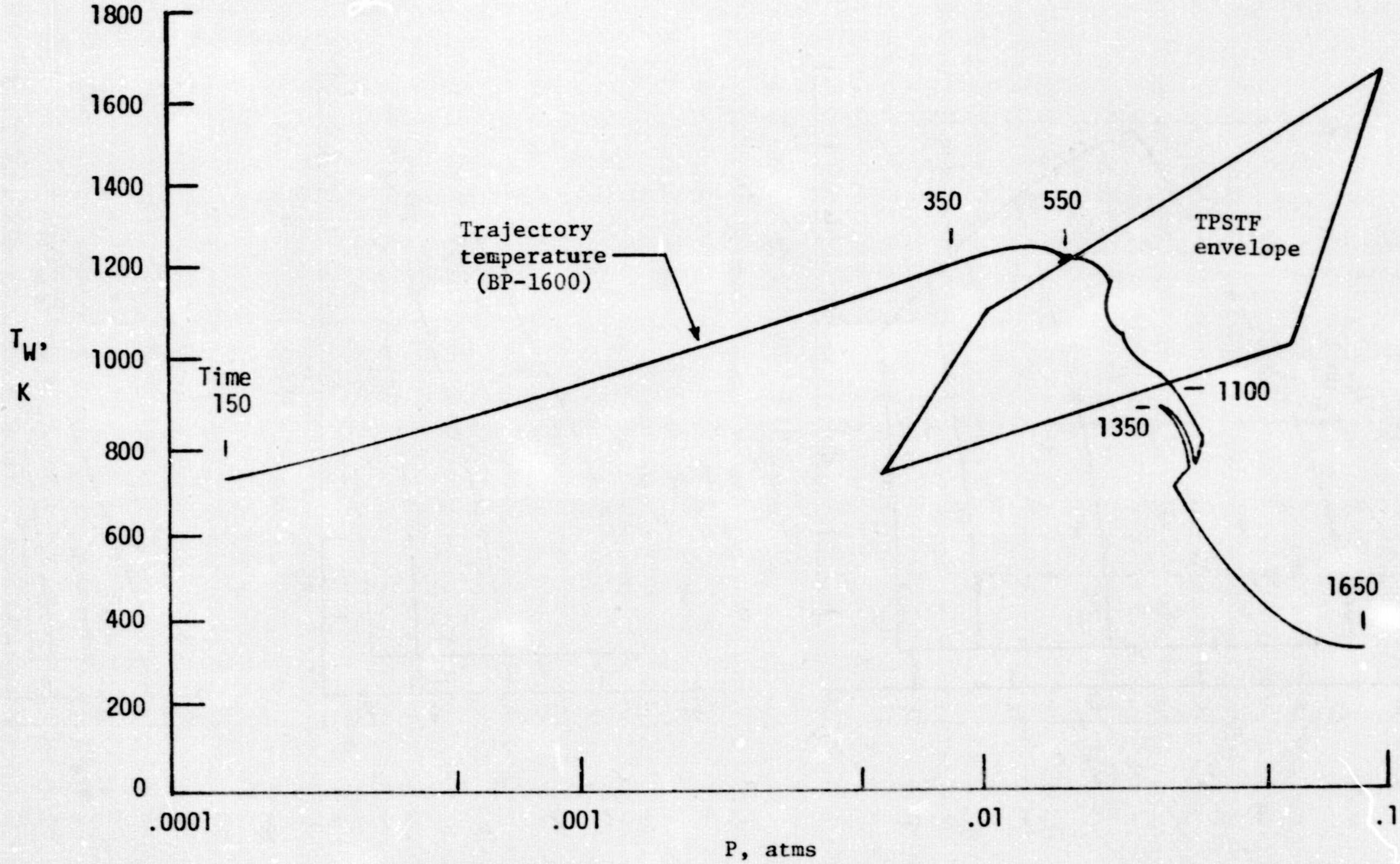
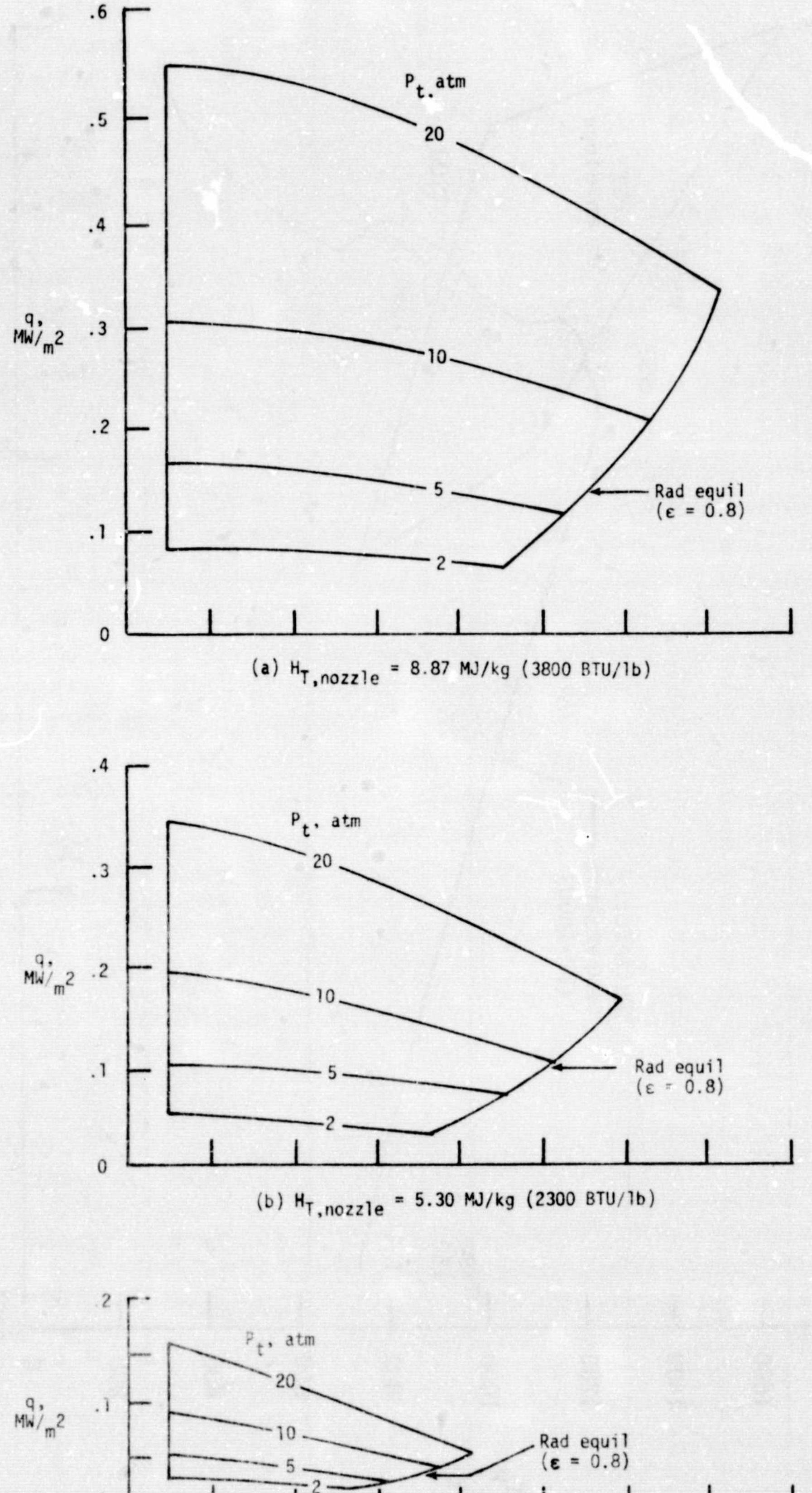


Figure 15. - Comparison of a shuttle orbiter temperature trajectory with the TPSTF operating envelope.



(c) $H_{T,nozzle}$ = 2.30 MJ/kg (1000 BTU/lb)

Figure 16. - Calculated heat flux as a function of panel surface temperature for various total pressures and enthalpy at the TPSTF nozzle.

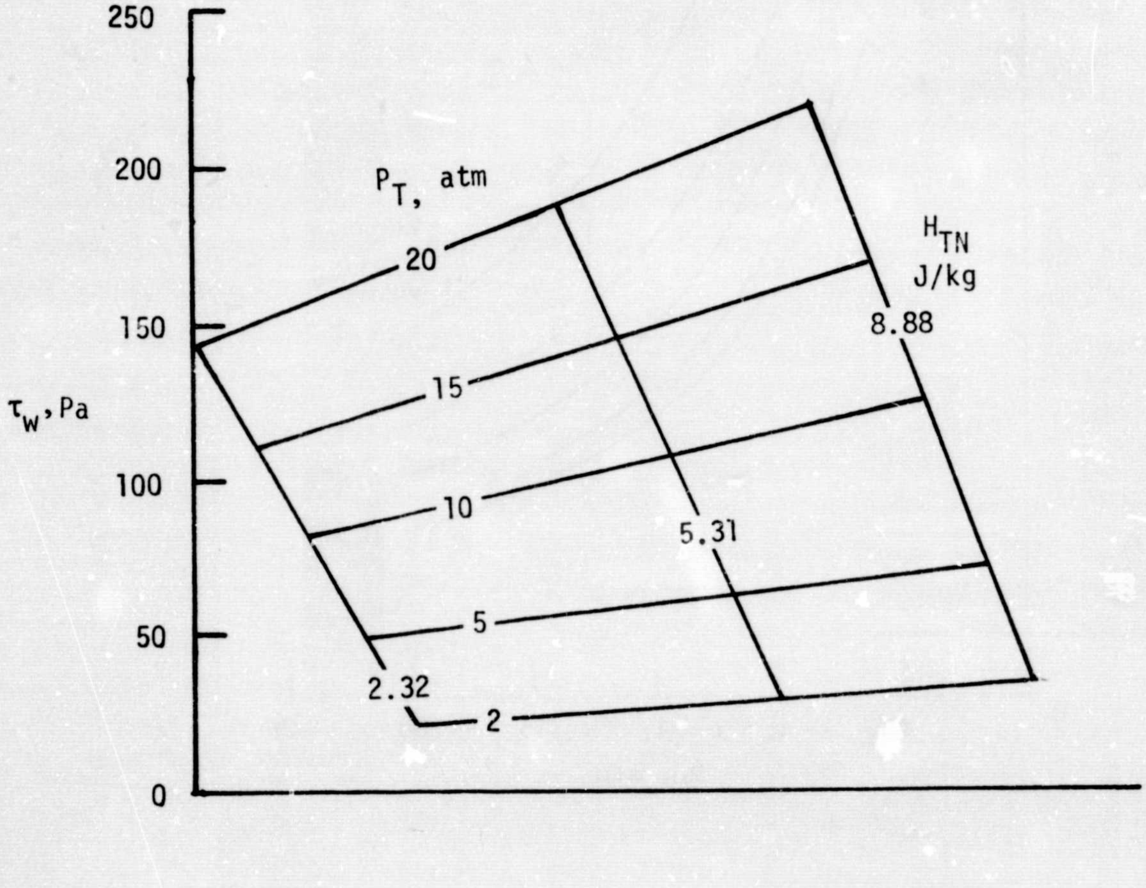


Figure 17. - Calculated shear forces on walls of test panels in TPSTF for range of operating pressures and nozzle total enthalpy .

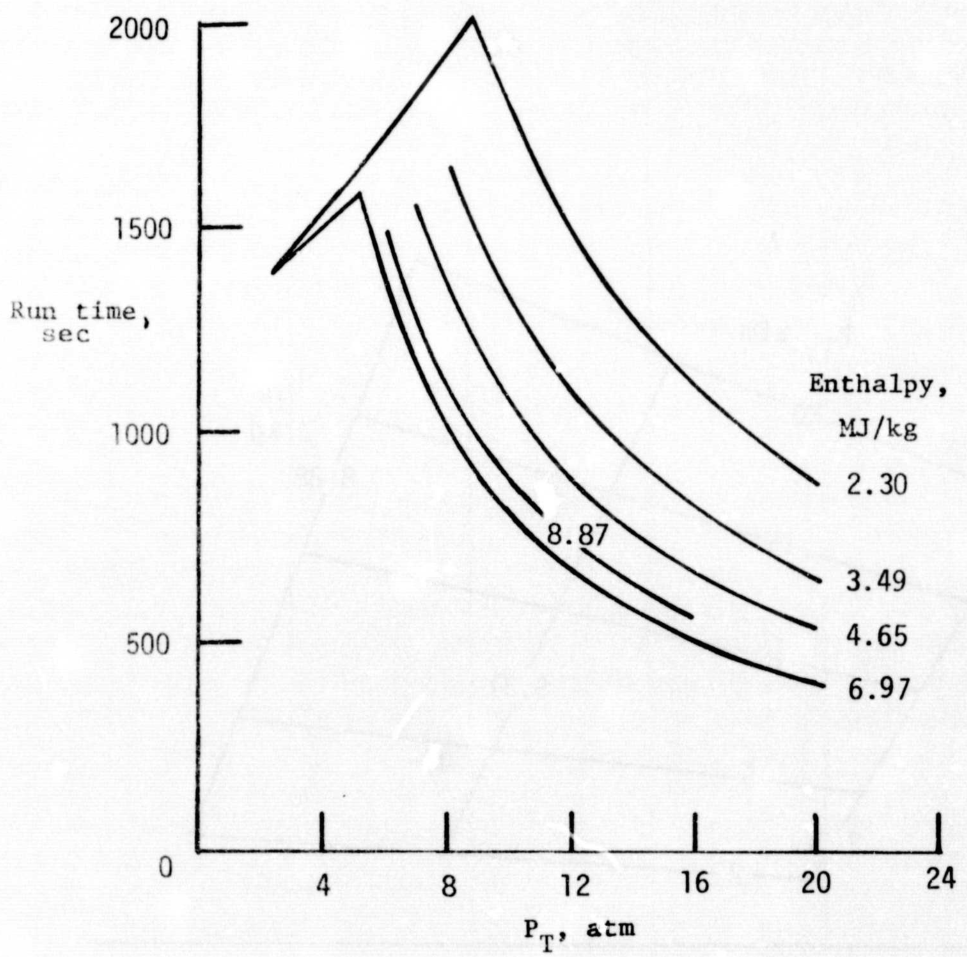


Figure 18. - Calculated TPSTF run times as a function of combustor total pressure.

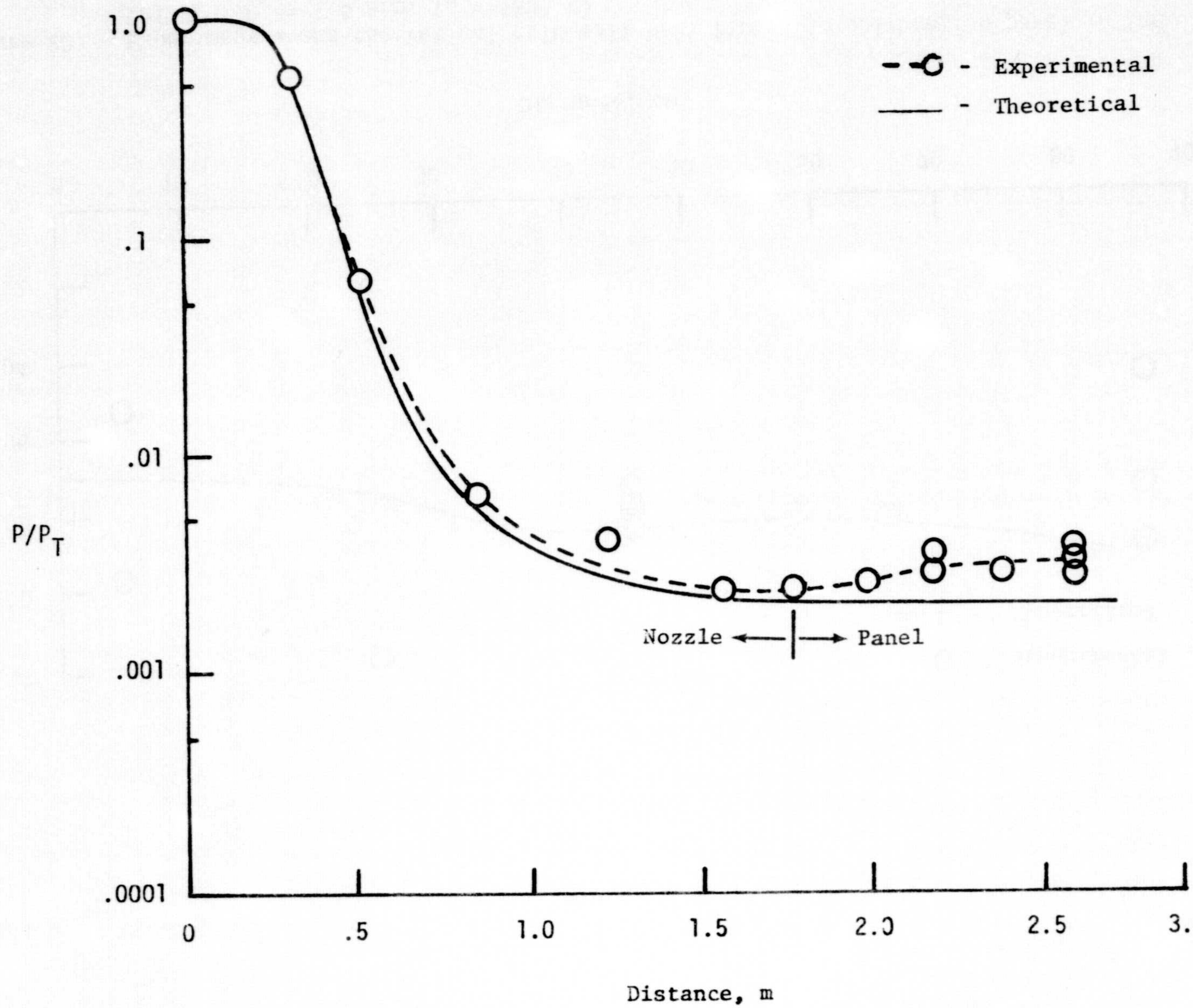


Figure 19. - Experimental and theoretical pressure ratios in the Langley TPSTF.

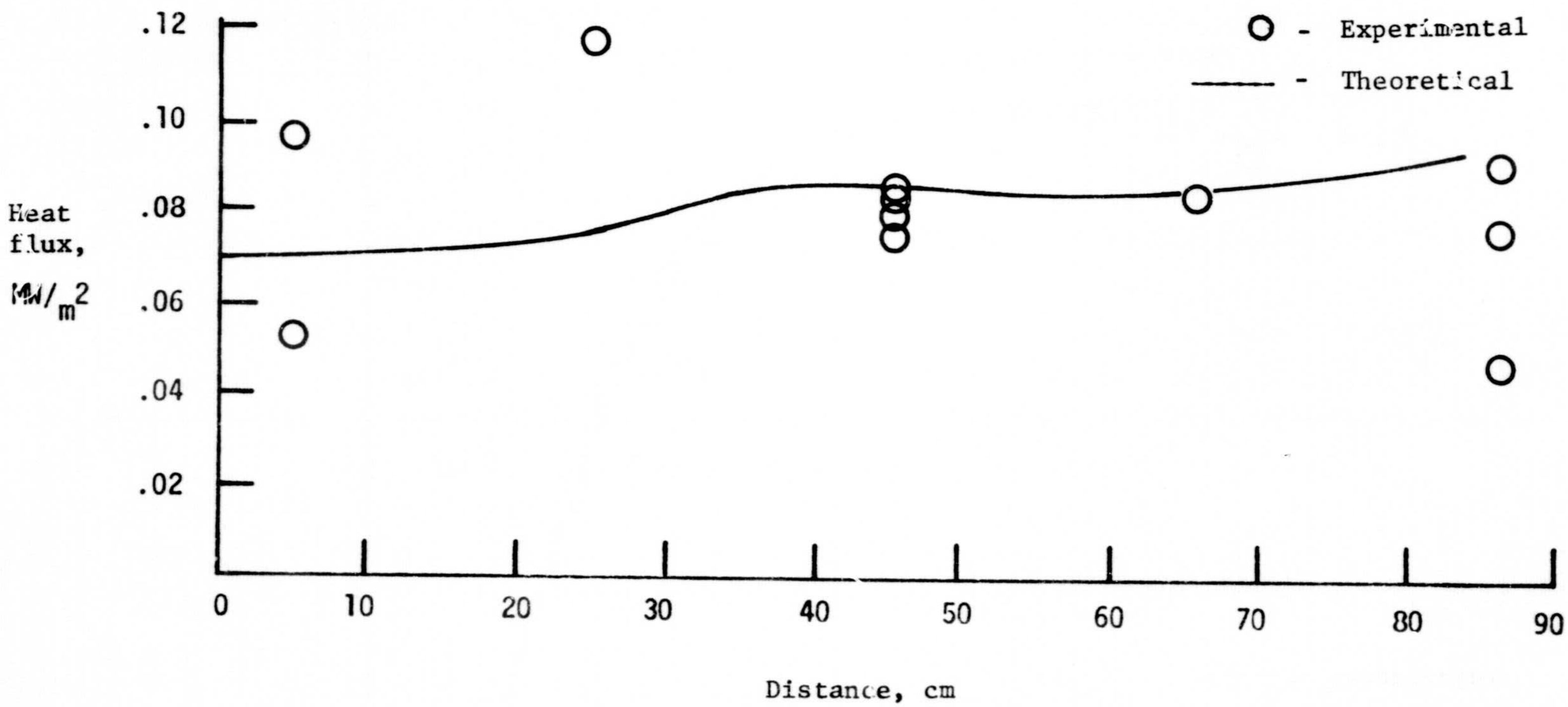


Figure 20. - Experimental and theoretical cold-wall heat fluxes to calibration panel in the TPSTF. (P_T = 7.4 atm, T_T = 1830 K)

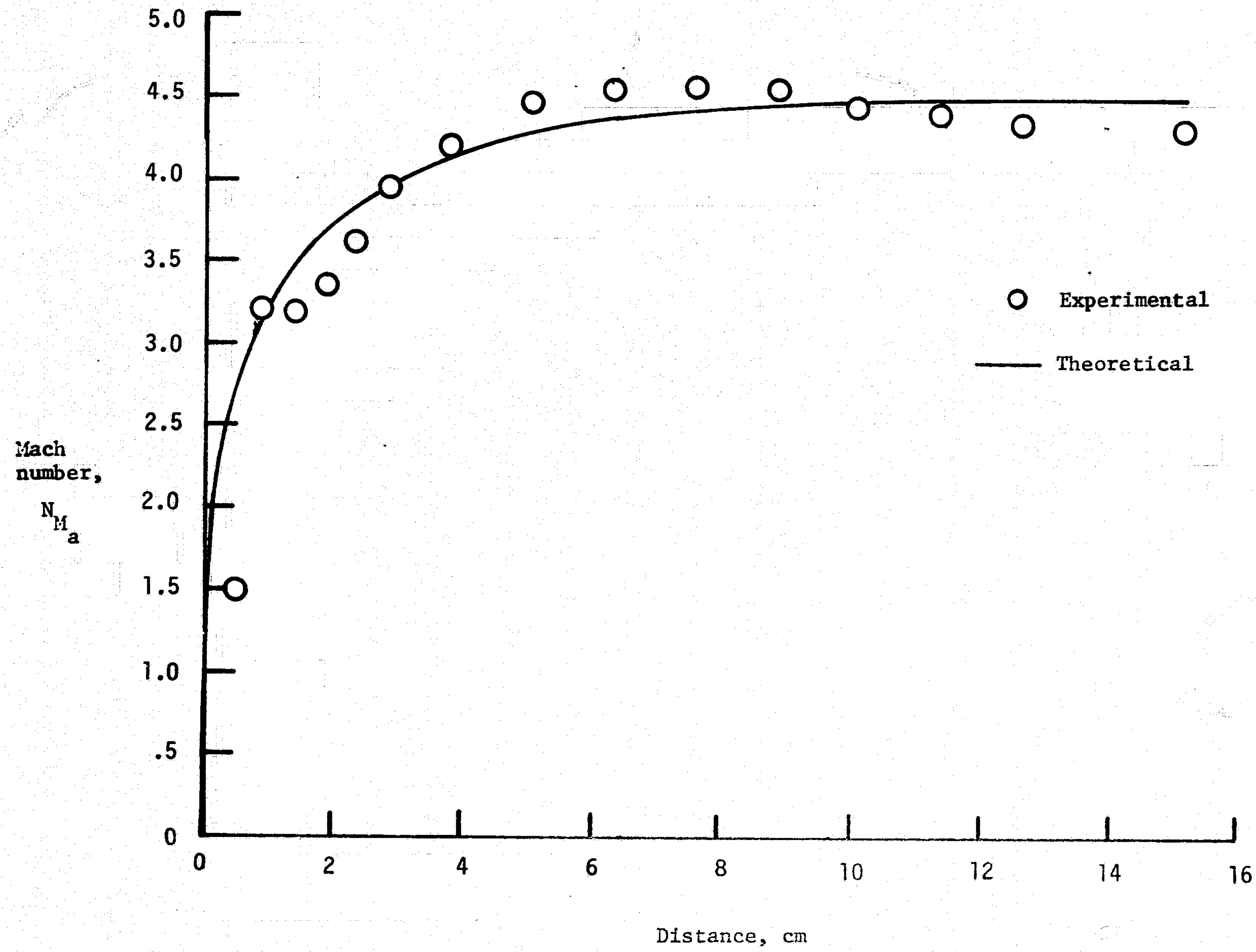


Figure 21. - Mach number distribution through boundary layer - test section of TPSTF.