THE NOL BOUNDARY LAYER CHANNEL

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THE NOL BOUNDARY LAYER CHANNEL

by

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ABSTRACT: A Mach 3 to 7 blow-down wind tunnel facility for investigating boundary layer phenomena in the transitional and turbulent range is described. The facility, referred to as the Boundary Layer Channel, utilizes a flexible plate and a flat plate to form the two opposite walls of a two-dimensional supersonic nozzle. The plate is 8 feet long. The channel operates at supply temperatures up to 1000°F and supply pressures from 0.1 to 10 atmospheres. The Reynolds number per foot capability is from 3×10^4 to 2.4×10^7.

U. S. Naval Ordnance Laboratory
White Oak, Silver Spring, Maryland

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The NOL Boundary Layer Channel

This report describes the design and performance of NOL's Boundary Layer Channel which has an operating capability in Mach numbers from 3 to 7 and in Reynolds number from 3×10^4 to 2.4×10^7 per foot. This work is part of a continuing program for the investigation of transitional and turbulent boundary layers and their related effects.

The authors wish to acknowledge the work of Dr. K. R. Enkenhus who did the aerodynamic design for the Boundary Layer Channel. They also extend their gratitude to members of the Wind Tunnel Design and Operations Division, in particular, the work of Messrs. L. Kaplan and R. Ogan for their efforts in providing the needed instrumentation which enabled the shakedown program to be carried out in an expedient manner. They also wish to thank Messrs. F. W. Brown and F. C. Kemerer for the efficient operation of the facility.

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Captain, USN
Commander

K. R. ENKENHUS
By direction

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SYMBOLS

B	constant used in equation (3)
h	nozzle exit height
M	Mach number
M_T	nozzle exit Mach number
p_e	diffuser exit pressure
p_o	supply pressure
p_o'	Pitot pressure
R_{ct}	nozzle throat radius of curvature
Re_θ	Reynolds number based on boundary layer momentum thickness
T	temperature
T_{aw}	adiabatic wall temperature
T_o	supply temperature
T_w	wall temperature
x	axial coordinate, measured from nozzle throat
X	dimensionless axial distance from nozzle throat, x/h
X_T	dimensionless distance from nozzle throat to beginning of test rhombus
y	coordinate normal to flat plate or axis
y^*	nozzle throat height
y^{**}	diffuser throat height
γ	ratio of specific heats
δ	boundary layer velocity thickness
δ^*	boundary layer displacement thickness
θ	boundary layer momentum thickness

INTRODUCTION

Many boundary layer studies in recent years have been devoted to the solution of problems associated with re-entry flight at high Reynolds numbers and Mach numbers. Considerable progress has been made in laminar boundary layer studies. This type of boundary layer may be considered well understood if one knows the chemistry and reaction rates and neglects rarefaction effects. Transitional and turbulent boundary layers, on the other hand, are not nearly as well understood. Reliable theoretical descriptions of transitional and turbulent boundary layers are not available at high Mach numbers due to a lack of understanding of the basic physical phenomena. There is also a lack of reliable and complete experimental data. Consequently, to further enhance the understanding of compressible boundary layer flows and to provide experimental data to assist theoretical predictions, the NOL Boundary Layer Channel was designed and fabricated.

NOL's Mach number 3 to 7 Boundary Layer Channel is essentially a continuously operating wind tunnel. The conventional symmetrical supersonic nozzle has been replaced by a nozzle having a flat test plate as one wall, a flexible plate as the other wall, and two slightly diverging side walls. The channel's instrumented flat test plate extends from the subsonic inlet to the supersonic diffuser. A desired distribution of local flow properties along the test plate can be achieved by setting the flexible plate contour. The test plate is 100 inches long and diverges from 12 inches at the nozzle throat to 13.5 inches at the nozzle exit. The channel uses the propane gas fired heater, bottled air supply, and vacuum system used previously by the NOL Hypersonic Tunnel No. 4 and reported in reference (1). The present report describes the facility and its performance at the nominal Mach number 5 nozzle setting.

MAJOR COMPONENTS OF THE BOUNDARY LAYER CHANNEL

A schematic diagram of the Boundary Layer Channel is shown in figure 1. The facility may be divided into two parts; namely, the supporting equipment and the channel itself. The supporting equipment, which is shared with other wind tunnel facilities at NOL, is described in references (1) and (2); however, a brief description is included herewith. The other part, the channel itself, is comprised of the settling chamber, nozzle, test plate, and variable diffuser. These will be described in detail.

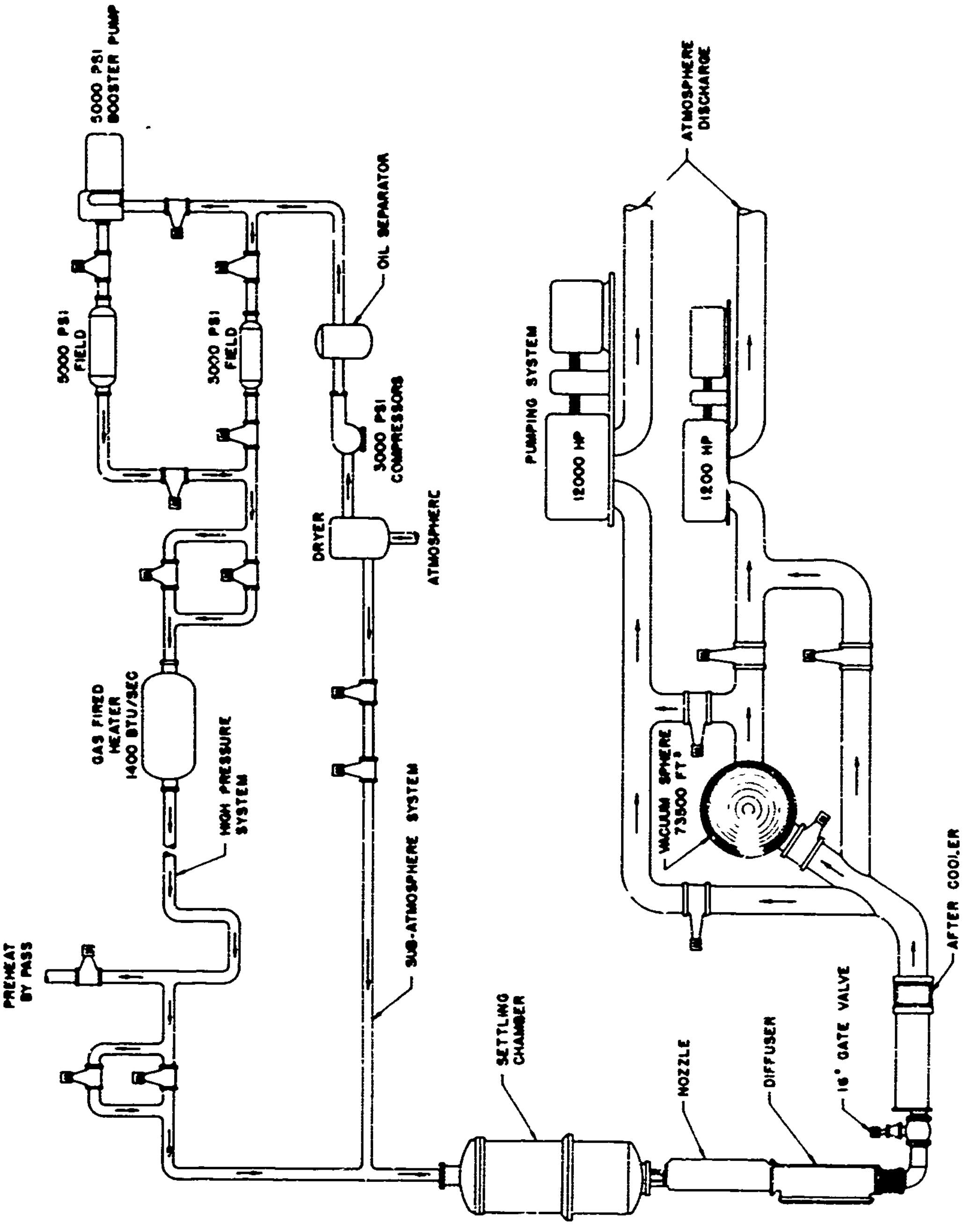

FIG. 1 SCHEMATIC DIAGRAM FOR NOL BOUNDARY LAYER CHANNEL

Supporting Equipment

The supporting equipment consists of the following: air drier, air compressors, air storage, pressure regulators, temperature controllers, exhaust piping, and vacuum pumps.

Air drying is accomplished principally by passing the air through a bed containing an alumina-type desiccant. Further drying is done in the compressor aftercoolers. The dew point can be in the range from -40°F to -73°F.

The supply air is compressed by twelve reciprocating compressors which have a combined delivery rate of 2.4 lbs/sec which pressurize a 2300 cubic foot reservoir to 3000 psi. Nine hundred cubic feet of the above reservoir can be further compressed to 5000 psi by a single compressor which has an output capacity equal to that of the twelve compressors.

Pressure regulation is accomplished in two stages for accurate control. Two pneumatically controlled, contoured plug valves first reduce the pressure from the 5000-3000 psi field to approximately 600 psi. The pressure is then further reduced to the maximum stagnation pressure of 150 psi by a second set of similar valves.

The system may also be operated subatmospherically by isolating the high pressure system and introducing the air directly from the air drying bed described previously. Control in this case is accomplished by a pneumatically operated butterfly valve.

The supply air is heated by a commercial, indirect-fired combustion heater utilizing propane gas. Maximum heating rate is 1400 Btu/sec at air weight flows between 4 and 28 lbs/sec with corresponding output temperatures of 1200°F and 200 F, respectively. Some temperature losses are sustained in the approximately 60 foot long piping leading from the heater exhaust to the settling chamber.

The air from the Boundary Layer Channel is exhausted into a 16 inch nominal diameter pipe, through a 16 inch gate valve, an aftercooler, and into the primary 36 inch diameter exhaust piping leading to the vacuum systems.

Two vacuum pumping systems are available. One system consists of four multistage centrifugal compressors each having a separate electrical motor drive with a combined rating of 12,000 horsepower. The nominal pumping speed is 90,000 cfm with a lower pressure limit of 5 mm Hg. This pumping plant is fully described in reference (2). The second system consists of seven rotary, sliding-vane pumps driven by four induction motors totaling 1200 horsepower. Pumping speeds vary between 7500 cfm and 22,500 cfm depending on pressure level. The low pressure limit is 2 mm Hg.

The Channel

Figure 2 is a layout of the test facility showing the general arrangement of the settling chamber, semi-flexible nozzle, and diffuser.

The settling chamber, shown in figure 3, is comprised of a large (80 inch diameter by 229 inches long) cylinder into which are mounted diffusion, filtering, and straightening screens as well as the contoured inlet to the nozzle. The cylinder is fully insulated on the inside surface, and is rated at 150 psi and 1000°F. The approximate weight is 10 tons. The incoming air is diverged outward from a duct whose diameter increases from 28 inches to 60 inches. The diverging section contains a series of fine mesh diffusion and filtering screens for a length of 31 inches. Dirt accumulation on the screens is monitored by a pressure system. A transition section is located immediately downstream of the screens in which the flow cross-section is transformed from circular to square. The remainder of the settling chamber contains more screens which diminish in mesh size and spacing as they approach the nozzle inlet. The largest has an opening of 3 x 3 inches and the smallest .0165 x .0165 inch as shown in figure 3. The additional screens are designed to minimize the turbulence level of the flow.

An entrance funnel is located between the settling chamber and the nozzle inlet to direct the air flow smoothly into the nozzle throat. Two entrance funnels were fabricated, one for operation at a nominal nozzle exit Mach number of 3 and the other at 5. The contour of each entrance funnel has been designed to blend smoothly with the contour of the nozzle inlet.

The flexible plate nozzle, shown in figures 4 and 5, consists of the following: fixed inlet, the flexible plate, flat plate, side doors, outer and inner frames, inlet flange, exhaust flange, the jacks and related equipment. Total weight of the assembly is approximately 4-1/2 tons.

The nozzle throat block, which has a fixed contour extending from the nozzle inlet to 5 inches downstream of the throat, and the flexible plate are fabricated as one unit. The throat block contains internal water cooling passages designed to operate at maximum throat surface temperatures of 500°F. In the flexible plate region where the aerodynamic heating is considerably lower than at the throat, cooling is provided through copper tubes soldered to the back of the plate. The tubing has not hampered the flexibility of the plate and provide sufficient cooling to protect the seals along the edge of the plate and to maintain dimensional stability.

The half-inch thick flexible plate, whose width diverges from 12 inches at the throat to 13.5 inches at the exit, is approximately 10 feet long. It is a floating element supported to the nozzle framework by heavy screw jacks. The upstream throat section is attached by means of a heavily ribbed assembly containing a slide and screw arrangement. This allows throat openings from 1/32-inch to 3 inches.

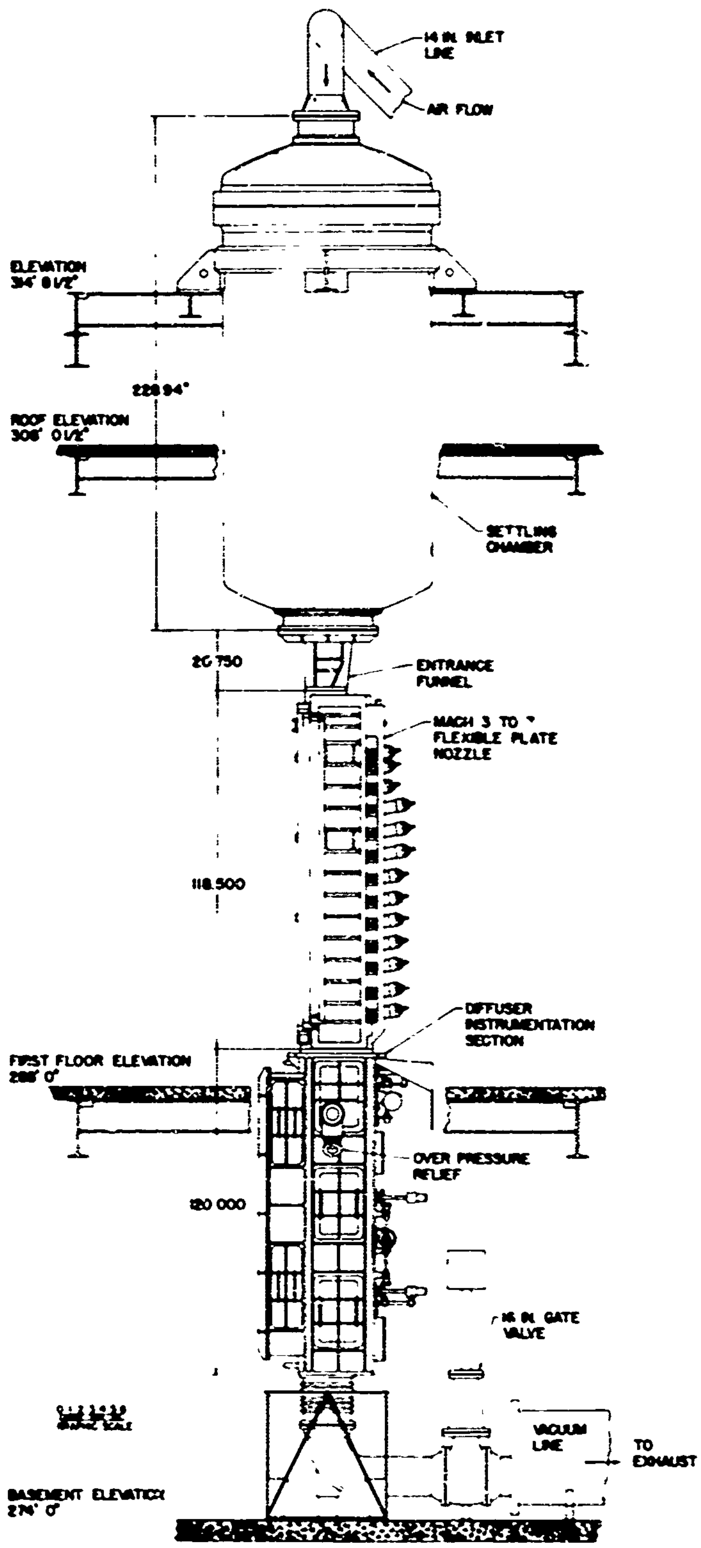

FIG. 2 GENERAL ARRANGEMENT OF BOUNDARY LAYER CHANNEL

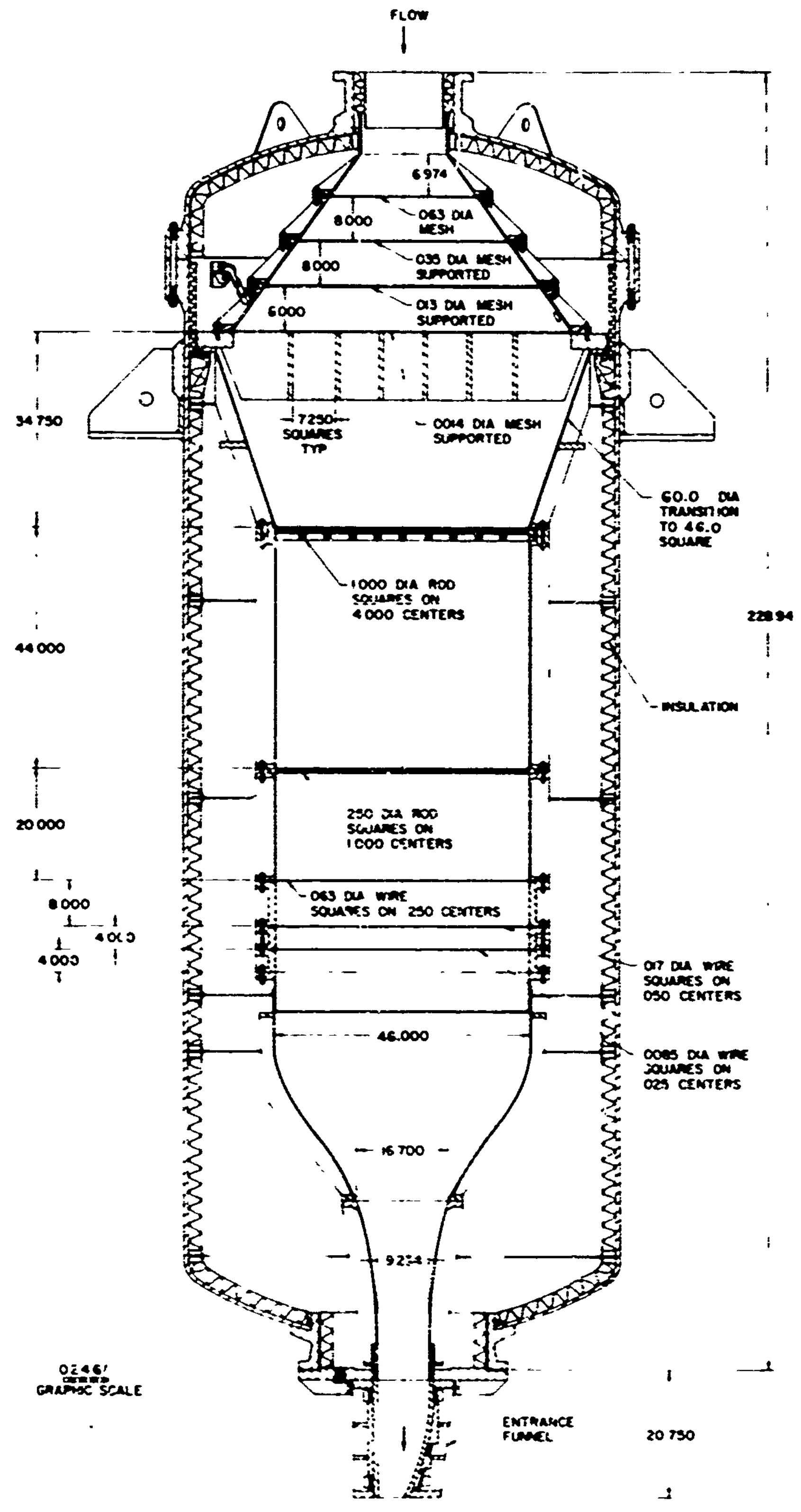

FIG. 3 BOUNDARY LAYER CHANNEL SETTLING CHAMBER

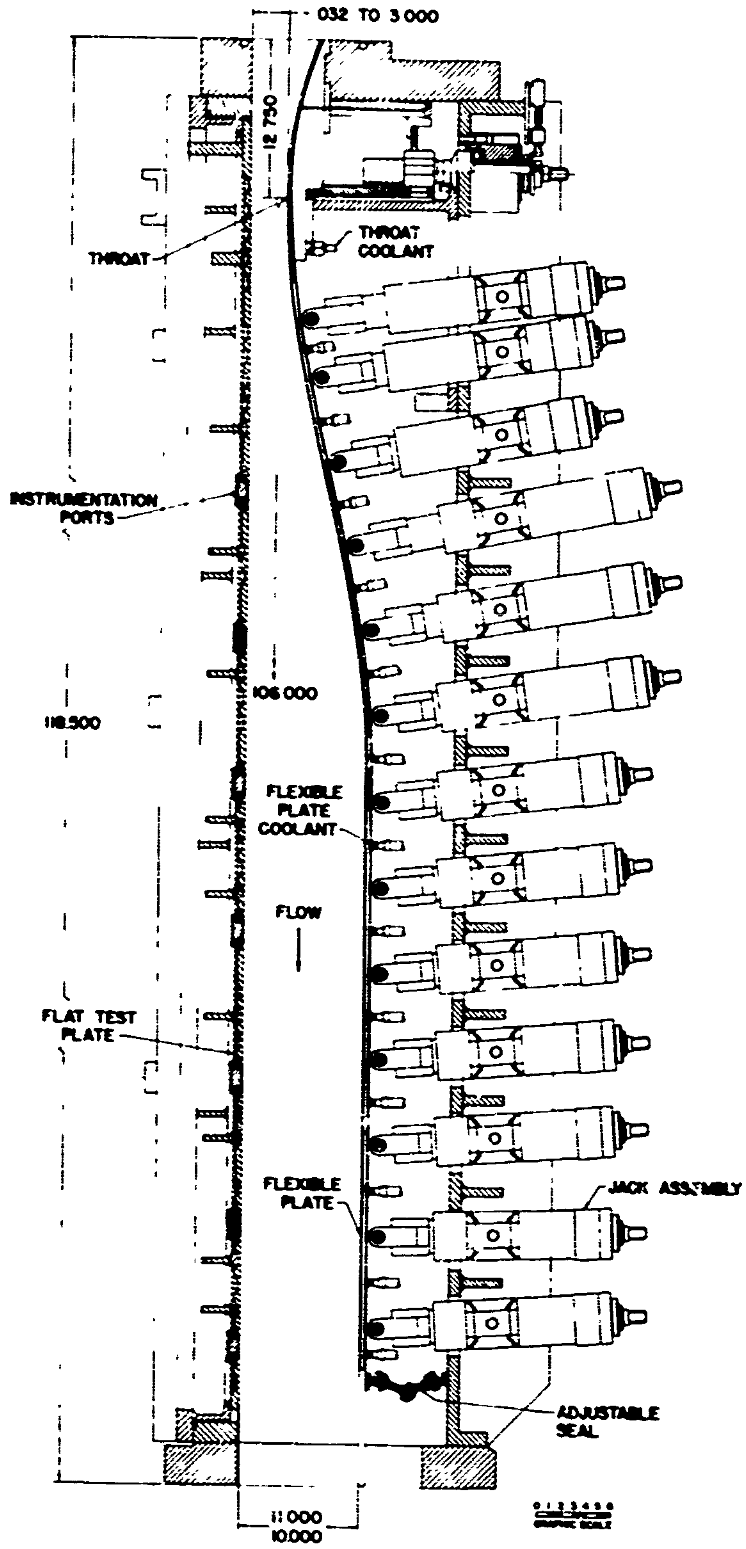

FIG.4 BOUNDARY LAYER CHANNEL FLEXIBLE NOZZLE

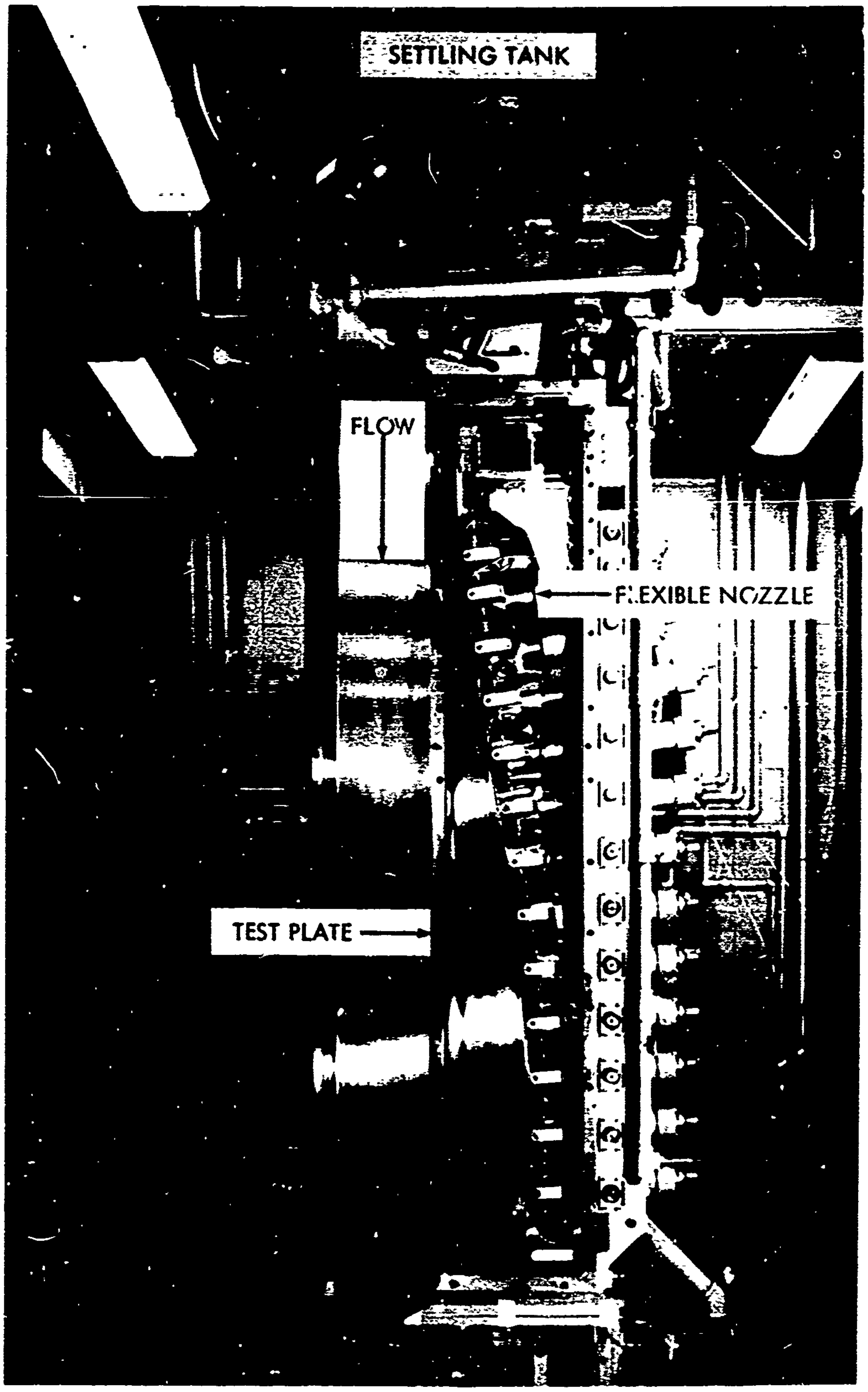

FIG. 5 N.O.L. BOUNDARY LAYER CHANNEL

Thirteen screw jacks spaced from 5 to 7 inches apart support and maintain the proper contour in the flexible plate. Each jack is hinge supported to the flexible plate and to the nozzle structure. Consequently, the jackscrews control only the distance between the two pivot supports and the jacks attain their own equilibrium angular positions. The jacks and the throat block are manually operated. Strain gages are located at each jack location to monitor the strain on the plate. The maximum strain limit is 92,000 psi.

Air tight seals are provided by "O" rings around the edge of the flexible plate and throat block. An adjustable web seal is used at the nozzle exit to allow for thermal expansion of the heated plate and to permit adjustments of the nozzle exit height between 10 and 11 inches.

The flat plate is a stainless steel weldment designed to operate at uniform temperatures up to 500°F. Cooling passages, separated into discrete compartments, were placed along the length of the plate. To maintain dimensional stability over this temperature range it was necessary to make the plate, in effect, a free floating body. This was accomplished by supporting the flat plate to an auxiliary frame by spring loaded clamps . At the upstream edge, the plate is butted flush to the entrance funnel by means of two screw jacks. An "O" ring seal is used between the mating sections here to prevent the high pressure air from by-passing the nozzle throat region. The two side edges of the plate are beveled and a wedge type seal is used to provide for thermal expansion.

Static pressure orifices of 1/32 inch diameter, were provided along the center of the plate at 2 inch intervals. In addition, instrumentation ports, 1-7/8 inches in diameter, are provided every 12 inches starting at a station 24 inches downstream of the nozzle throat.

The doors are stainless steel weldments, hinged to the primary framework and water-cooled. Static pressure orifices are also provided in the downstream portion of one door. These orifices are located 4 inches apart and 3.5 inches from the flat plate. The doors are designed for maximum deflection of .0015 inch and each weighs approximately 600 pounds. The doors align the flexible plate and they are bolted to the primary framework during a test.

Figure 6 illustrates the variable plate diffuser. It is a non-symmetrical, two-dimensional flow duct utilizing hinged plates which can be positioned to form a converging-diverging configuration with a parallel throat. The width of the diffuser plate is 13 inches and the overall length is 10 feet with the convergent portion occupying 40 percent of the length. The upstream plate is attached at the inlet to a pivot which is positioned by an electric motor to align the leading edge of the plate with the opening of the nozzle. A second motor adjusts the opening of the parallel diffuser throat. The angle of the subsonic diffuser plate is maintained at four degrees. A flexible seal attached to the back of the second plate prevents recirculation of the air flow. All walls of the diffuser exposed to the air flow

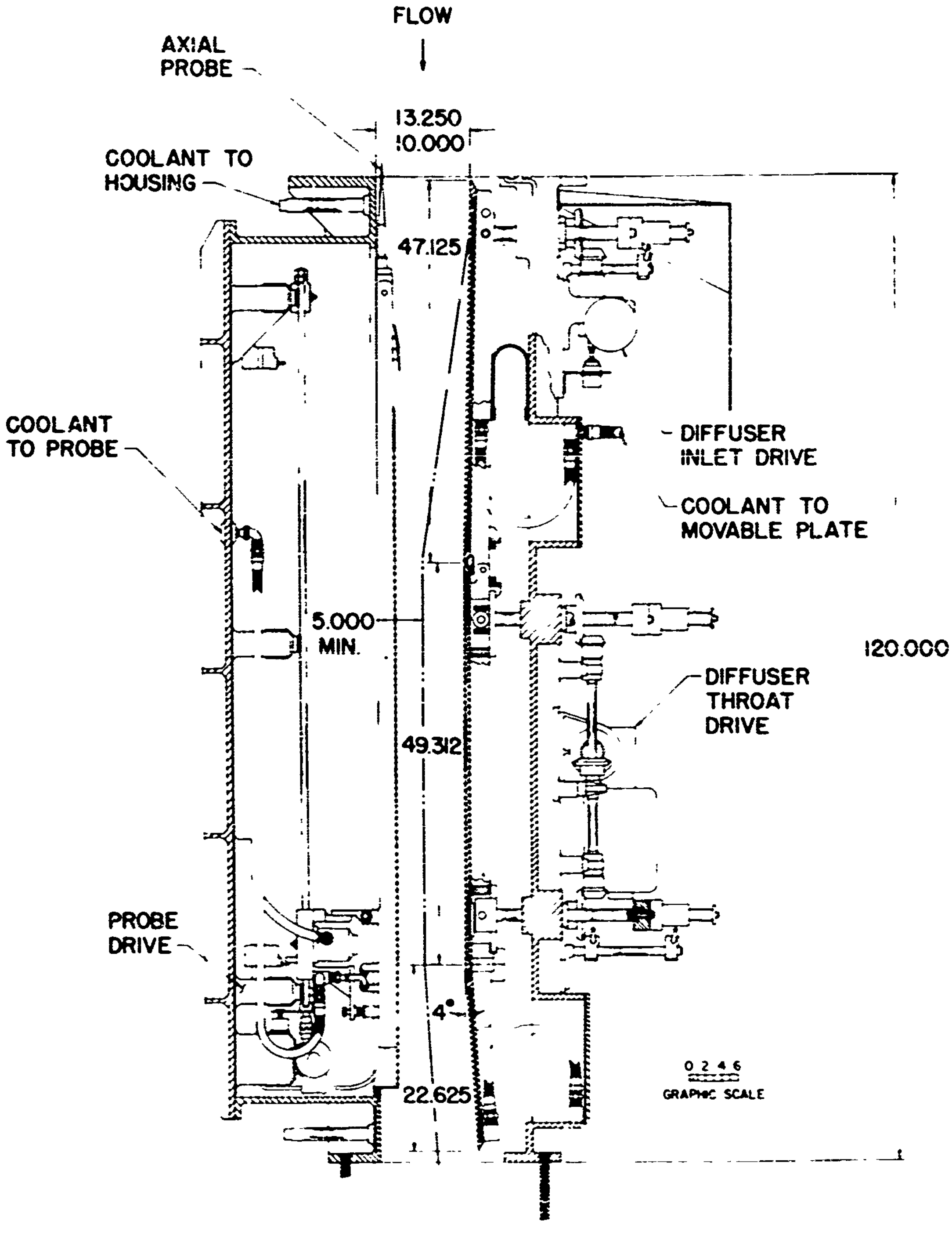

FIG.6 BOUNDARY LAYER CHANNEL DIFFUSER

have internal coolant passages to protect the plate and the seal arrangement.

The straight wall of the diffuser has a 1-1/2 inch wide by 2 inch high rectangular cross-section channel along its center line. This channel houses the axial drive mechanism which will be discussed later.

Nozzle Contours

The flexible nozzle plate was fabricated as an integral part of the rigid throat block. The contour of the subsonic inlet portion of the throat block is defined by the quintic:

$$y = (8.9891 \times 10^{-7})\, x^5 - (7.0954 \times 10^{-5})\, x^4 + (1.3418 \times 10^{-3}\, x^3 + .008\, x^3 \qquad (1)$$

$$\text{for } [-12.75 \leq x \leq 0]$$

The coordinates (x,y) are in inches and are (0,0) on the throat block at the minimum area cross section. The contour of the supersonic portion of the throat block is defined by the cubic:

$$y = -\,(1.1905 \times 10^{-4})\, x^3 + .008\, x^2 \qquad (2)$$

$$\text{for } 0 \leq x \leq 5$$

The latter is derived from the following boundary conditions:

$$x = 0,\ y = 0,\ R_{ct} = 62.5'' = \frac{d^2y/dx^2}{\left[1 + \left(\frac{dy}{dx}\right)^2\right]^{3/2}}$$

$$x = 22.4'',\ \text{wall angle} = 10 \text{ degrees} = \tan^{-1}\left(\frac{dy}{dx}\right)$$

The method selected for calculating the flexible plate contour is identical to the two-dimensional flow design procedure used for rigid block nozzles employed in the other NOL facilities (refs. (3), (4), and (5)) and which is coded for the IBM 7090 high speed computer. Essentially the method needs a prescribed center line Mach number distribution from which a potential flow wall contour is computed by the method of characteristics. In the Boundary Layer Channel, the flow along the test plate is the flow prescribed along the center line of the conventional supersonic nozzle. The design procedure includes a laminar, transitional, or turbulent boundary layer correction by the methods used in references (4), (6), and (7), respectively, to produce the final geometric contour.

In applying this design method to the channel configuration, the center line Mach number distribution used in reference (5), namely,

$$M = M_T - \frac{M_T - 1}{X_T^2} (1 + BX)(X - X_T)^2 \qquad (3)$$

seems to be satisfactory. Equation (3) shows that the nozzle design variables are limited to M_T, X_T, and B. The coefficient B is determined by the values of R_{ct}, y* at M = 1 in equation (3) and also M_T and γ. Among the above variables only R_{ct} and γ are fixed quantities. Two of the remaining three quantities, namely, M_T and X_T must be adjusted such that the completed nozzle contour with the boundary layer corrections matches the physical nozzle opening at the downstream end of the rigid throat block (at x = 5 inches) for the desired nozzle throat opening, y*. The nozzle is designed iteratively for a desired exit Mach number M_T, by initially assuming a nozzle core height of 8 inches from which the nozzle throat opening, y*, can be determined using isentropic flow tables. The length of the test rhombus can be computed knowing M_T. X_T is then the dimensionless distance from the nozzle throat to exit, less the length of the test rhombus and less any desired uniform flow length. These three quantities, M_T, X_T and y* plus the two fixed quantities are sufficient input to the computer program to calculate a potential flow contour. This contour together with the assumed operating supply temperature and pressure and the type of boundary layer flow, i.e., laminar, transitional, or turbulent, are then used in a second computer program to calculate the boundary layer displacement thickness δ^*, on both the flat plate and the flexible plate surfaces. The combined 8 inch exit core height plus boundary layer corrections are then compared with the physical nozzle exit opening. The procedure is then repeated with a different exit height assumption such that the exit height together with the boundary layer correction is within the limits of the range of the physical nozzle exit opening. The value of X_T is then adjusted until the computed nozzle opening at the 5 inch station (including boundary layer corrections) agrees with the physical opening of the nozzle throat block. The final constants in equation (3) for the Mach 5 nozzle setting are: B = .0234, M_T = 4.8, and X_T = 6.44. The computed boundary layer growth on both plates is shown in figures 7, 8, and 9 for operations at supply temperatures of 1000°R and supply pressures of 1, 5, and 10 atmospheres, respectively.

Adjusting the flexible plate to the computed contour is a tedious process because the jacks give the correct setting only at discrete points and the contour between these points assumes an equilibrium position in accordance with the stresses on the plate. Strain was monitored during the setting procedure and was found to be within the

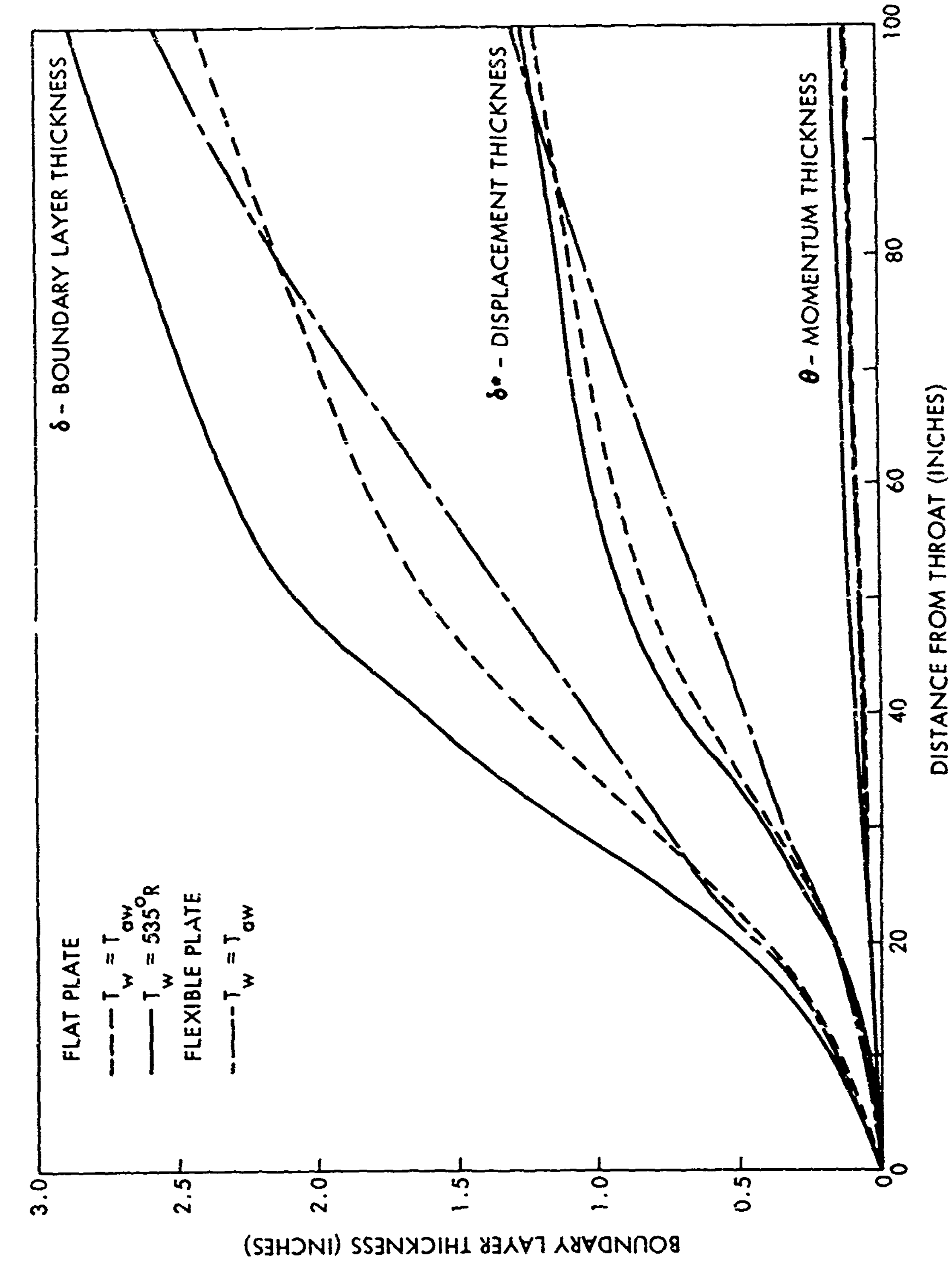

FIG.7 COMPUTED BOUNDARY LAYER GROWTH FOR MACH 5, $P_o = 1$ ATM, $T_o = 1000^\circ R$

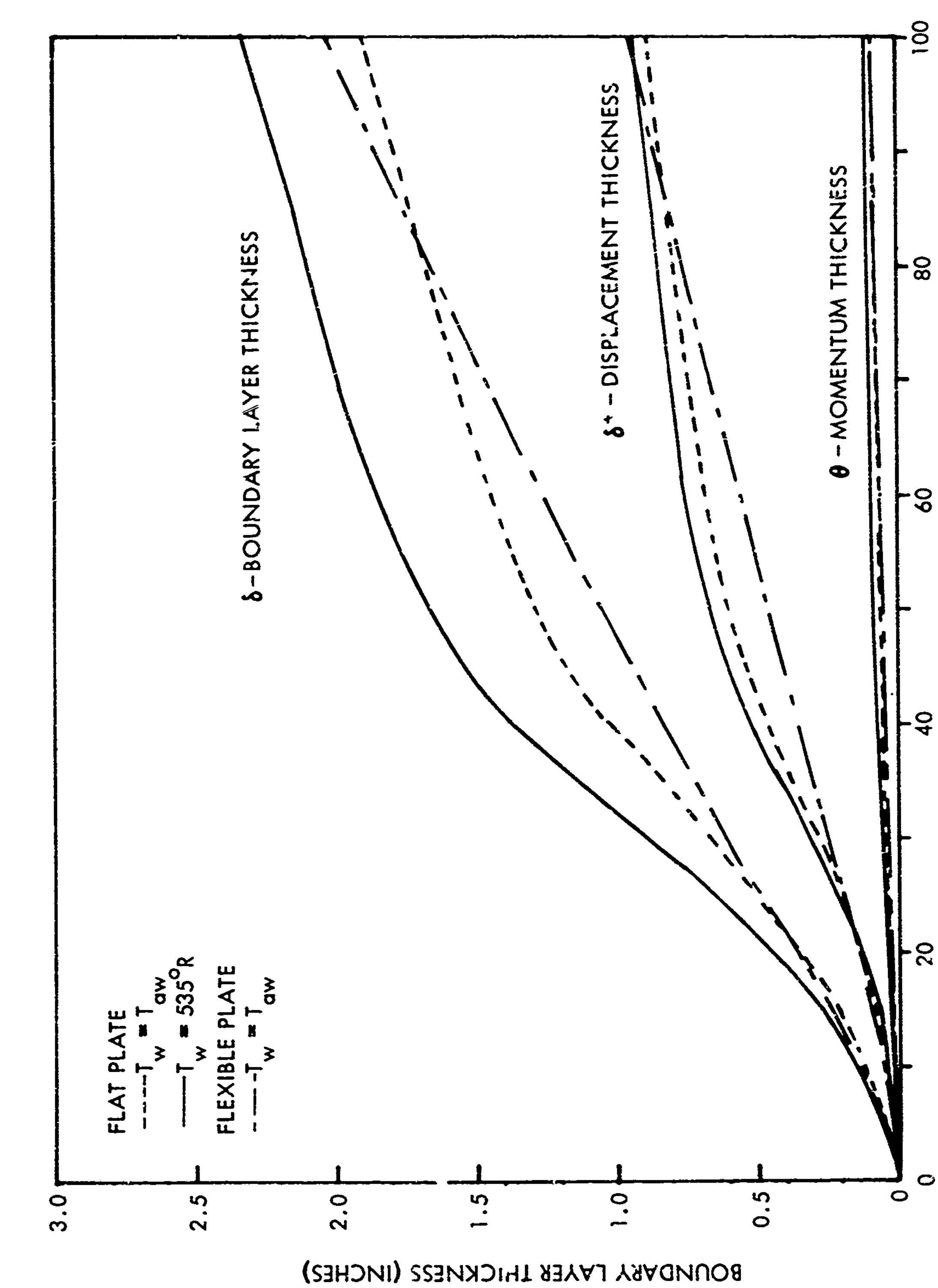

FIG.8 COMPUTED BOUNDARY LAYER GROWTH FOR MACH 5, P_o = 5 ATM, T_o = 1000°R

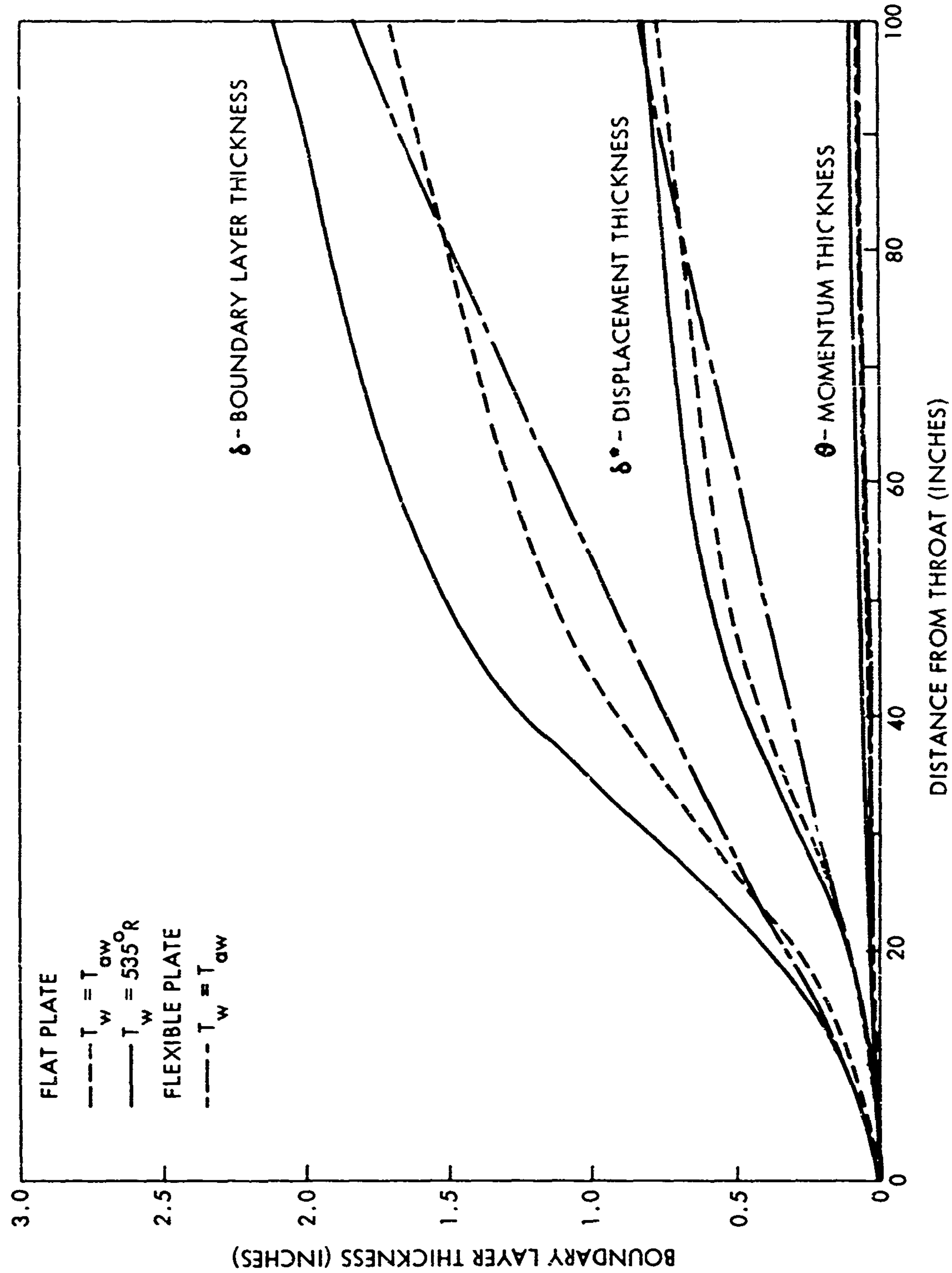

FIG. 9 COMPUTED BOUNDARY LAYER GROWTH FOR MACH 5, P_o = 10 ATM, T_o = 1000°R

specified structural limits. The contour of the flexible plate was set for supply conditions of 5 atmospheres and 1000°R which are considered to be median operating conditions. The actual adjustment of the plate was done as follows. The flexible plate was initially adjusted to the computed contour at each jack location. The uniformity of the flow was then measured with a Pitot probe driven axially in the freestream. The most severe compression waves detected were traced back to the contoured wall by a straight line projection of the disturbance at the direction determined by the local Mach angle. The nearest jack was adjusted to minimize the disturbance. The process was repeated until sufficient flow uniformity was obtained. It was found that the adjustment of a jack affected the contour at distances as much as three jack locations away and causes a corresponding change in measured flow conditions.

The final nozzle contour coordinates were measured at one inch increments using a specially designed instrument whose measuring accuracy is less than .002 of an inch. The measurements are compared with the computed contour and the differences are shown by the dashed line in figure 10. Measurements at the jack locations (circled points) show a systematic displacement from the computed contour. Measurements between jack locations show a different systematic displacement from the computed contour and also show that relatively sharp bending occurs near the jack location.

At the end of six months of operation the contour of the flexible plate was again measured, completely released and reset to the initial flow calibrated (final) contour setting. This was done by adjusting each successive jack to the calibrated setting, starting with the most upstream jack and working downward. The results are also shown in figure 10. The change in nozzle contour in six months can be as much as 0.020 inch as shown by the dot-dashed curve. The reset contour as compared with the computed contour is shown by the solid curve. Adjusting the flexible plate to a prescribed contour requires many readjustments of the screw jacks. This is so because by moving one jack setting, the angular position of neighboring jacks changes and in turn the coordinates of the plate at the neighboring jack stations is not identical to the original final contour. The differences can be seen by comparing the solid curve and dashed curve in figure 10.

The measured stress at each jack location, as anticipated, is greater upstream where the radius of curvature is smaller. The stresses can be monitored during the test. Table I is a summary of the typical stress measurements recorded at selected operating supply pressures.

INSTRUMENTATION

Axial Drive

In order to investigate the flow distribution along the flat plate an axial probe drive mechanism was installed within the tunnel (see also discussion of diffuser). This mechanism is powered by an

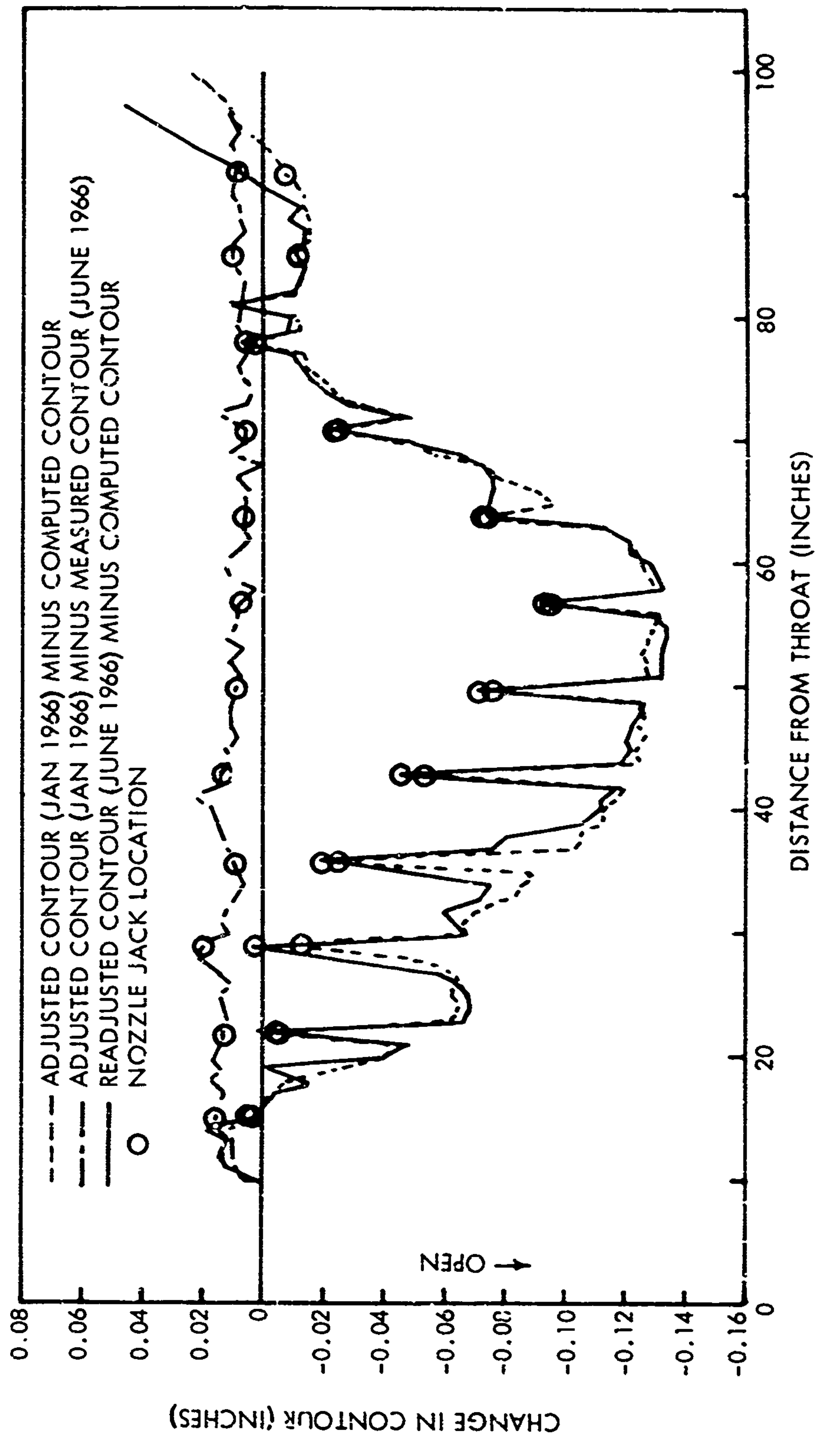

FIG.10 CHANGES OF FLEXIBLE PLATE NOZZLE CONTOUR

TABLE I

STRAIN GAGE MEASUREMENTS ON FLEXIBLE PLATE*

Gage No.	0	1	2	3	4	5	6	7	8	9	10	11	12
Distance From Throat (In.)	10	15	22	29	36	43	50	57	64	71	78	85	92
Static Reading	40.5 C	80.7 C	76.2 C	12.9 C	62.4 T	32.4 T	38.2 T	28.6 T	13.2 T	5.70 T	22.8 T	19.2 T	5.55 T
Under Vacuum	40.5 C	79.8 C	74.8 C	13.0 C	64.5 T	34.6 T	38.7 T	31.5 T	13.2 T	7.95 T	24.0 T	21.6 T	5.10 T
P_o = 10 atm	33.3 C	62.1 C	82.2 C	13.5 C	62.1 T	33.0 T	36.6 T	30.0 T	10.8 T	6.00 T	22.4 T	--	2.70 T
P_o = 5 atm	34.4 C	78.8 C	81.0 C	15.8 C	62.2 T	33.6 T	36.6 T	30.3 T	11.2 T	6.75 T	22.4 T	--	3.45 T
P_o = 1 atm	39.6 C	72.5 C	76.8 C	13.4 C	64.2 T	35.4 T	38.4 T	31.5 T	13.0 T	7.95 T	23.8 T	--	4.80 T

* 10^3 lb/in^2

C = Compression

T = Tension

electric motor housed in the diffuser casing. Probe speed and distance traveled are controlled by the channel operator. The axial distance is read out through a servo-system and recorded automatically. The drive mechanism can be used to support as many as five probes at various distances from the flat plate. An airfoil mounted behind the probes is designed to give negative lift which keeps the drive mechanism pressed against the testing surface. Copper rollers are spring mounted at the sides of the probe support enabling the mechanism to glide smoothly along the tunnel walls. The maximum travel along the flat plate is about 50 inches.

Boundary Layer Traverse

For boundary layer profile surveys an electrically operated water-cooled micro-traverse has been designed for use at several stations on the test plate. Total travel of the traverse is 2.50 inches. The traverse design permits two probes to be used simultaneously. Location of the traverse mechanism is obtained directly from a dial counter which can be read with an accuracy of ± 0.001 inch or from a digital voltmeter with an accuracy of ± 0.0005 inch.

Boundary Layer Probes

In order to determine the flow properties through the boundary layer, three quantities must be known; the static pressure, Pitot pressure, and total temperature. Usually the static pressure is assumed to be constant through the boundary layer and equal to the wall pressure. Presently, the Pitot pressures are being measured with small probes made from 0.125 of an inch stainless steel tubing flattened at the tip to a rectangular opening with a half-height of 0.010 of an inch. An equilibrium conical temperature probe (ref. (8)) is used to determine the stagnation temperature through the boundary layer. Probe pressures are read out directly from mercury and oil manometers or are measured with pressure transducers. Probe temperatures are recorded on a variable span strip chart recorder and on the PADRE (Portable Automatic Data Recording Equipment), reference (9).

Hot Wire Anemometer

A Shapiro-Edwards Model 50 Constant Current Hot Wire Anemometer system is available to investigate the fluctuating quantities of the hypersonic turbulent boundary layer.

Skin Friction Balance

An important part of boundary layer research is the determination of skin friction. Many investigators have obtained skin friction measurements from measured velocity profile gradients. Much controversy has arisen as to the accuracy of the data obtained in this manner.

It is felt that a comparison should be made between skin friction coefficients obtained using a skin friction balance and those obtained from profile measurements. There have been some data published showing such a comparison, i.e., reference (1). In this particular reference most of the data were obtained under adiabatic wall conditions. A comparison of data with heat transfer is obviously needed. A skin friction balance has been designed at NOL to obtain direct measurements of skin friction (refs. (11) and (12)), see figure 11. The balance is designed for measurements in the presence of heat transfer and pressure gradient.

Data Handling

Presently, the boundary layer data are recorded automatically and continuously on NOL's PADRE which is described in reference (9). This unit provides seven channels with servo-systems and direct digital conversion to IBM cards. The IBM card output is used directly with NOL's IBM 7090 computer for the data reduction programs. Several programs are available for reduction of the various tests made in the channel. The use of an automatic plotter expedites the interpretation of the recorded data.

PERFORMANCE

The temperature and pressure operating envelope of the Boundary Layer Channel at the Mach number 5 nozzle throat setting is shown in figure 12. Also shown are the air mass flow rate and the operating time required to deplete the air supply reservoir. The temperature drop measured in the Boundary Layer Channel is greater than previously reported for the NOL Hypersonic Tunnel No. 4, reference (1), due to the longer lengths of piping and the more massive settling tank. The temperature drop becomes greater at lower mass flow. It was not possible to sustain continuous supersonic flow at supply pressures below four atmospheres with the rotary vane vacuum pumping system described earlier.

The performance envelope is extended to the Mach number 3 operating conditions by assuming the same heater output efficiency for the same air mass flow rates and pressures. This is shown in figure 13. At high mass flow rates which are well beyond the original intended range of the heater, very little temperature gain can be expected.

Temperature uniformity of the subsonic inlet flow in the entrance funnel is shown in figures 14 and 15. These measurements were made with the standard subsonic total temperature probe described in reference (13). The survey method employs a probe which spans the two opposite walls; the north-south being the side walls, the east-west being the flat plate and the contoured surface. A second total temperature probe placed at a fixed point away from the surveying region, was used as the reference temperature. This reference temperature measurement removed the uncertainty of the variation of supply temperature with time.

ACCURACY: ± 5% AT 20 MG
1% AT > 20 MG

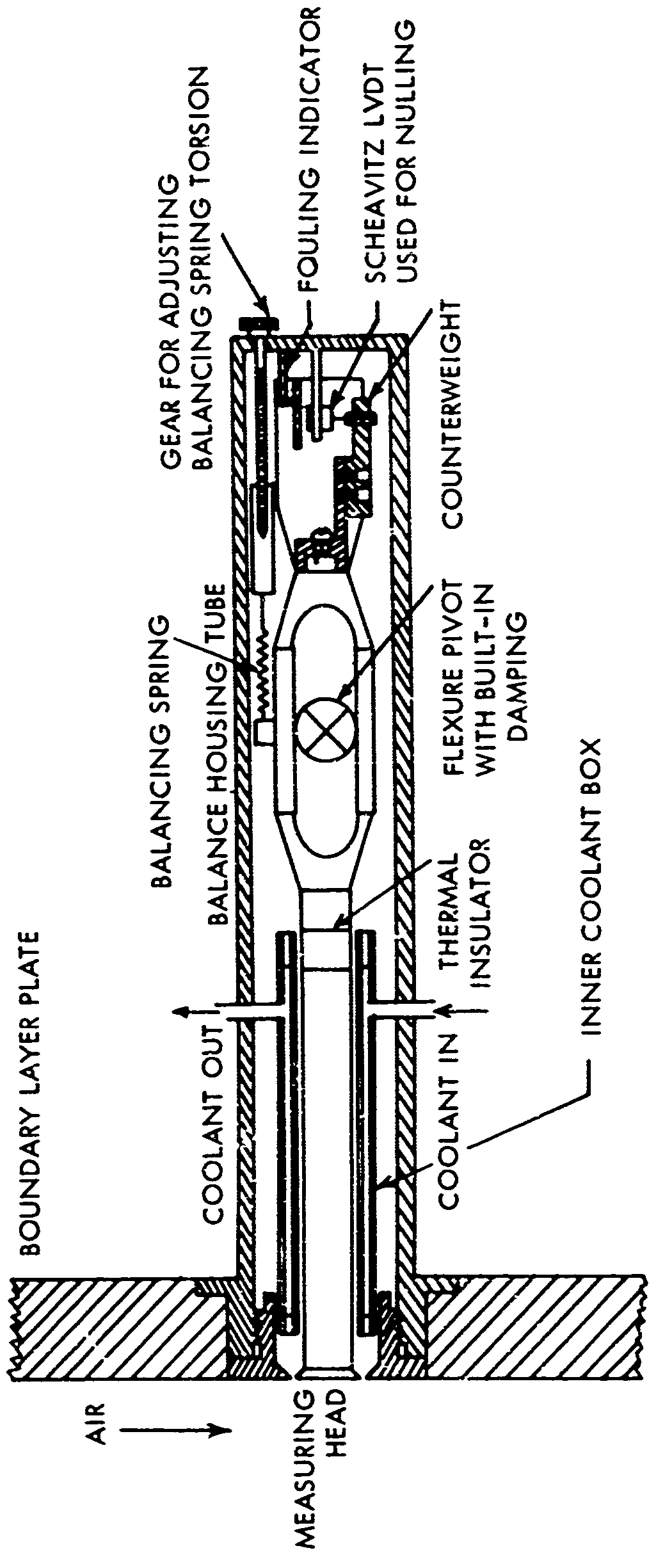

FIG.11 SCHEMATIC SHOWING OVERALL LAYOUT OF THE SKIN FRICTION BALANCE

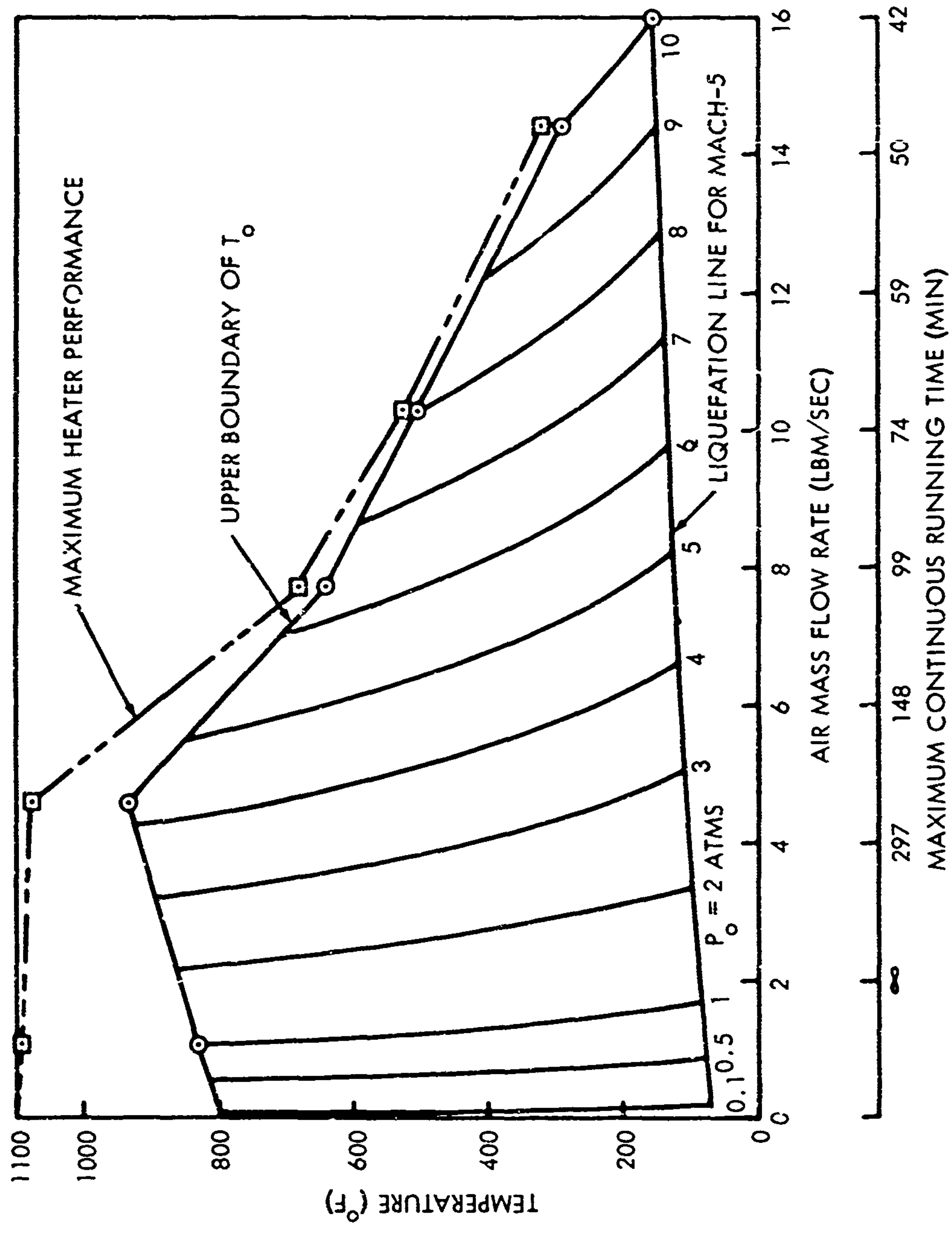

FIG.12 OPERATING ENVELOPE FOR THE BOUNDARY LAYER CHANNEL, MACH 5

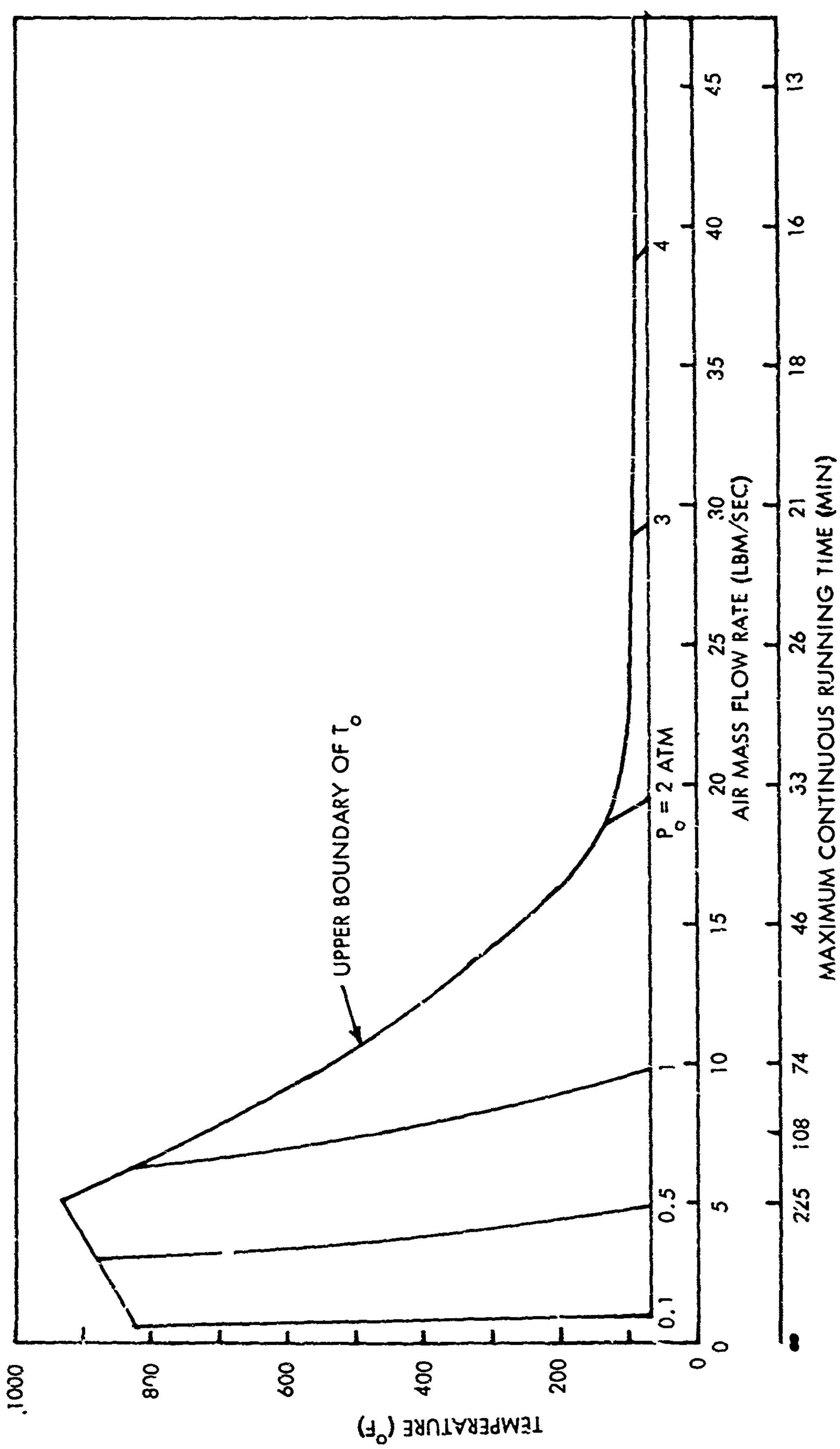

FIG. 13 OPERATING ENVELOPE FOR THE BOUNDARY LAYER CHANNEL, MACH 3

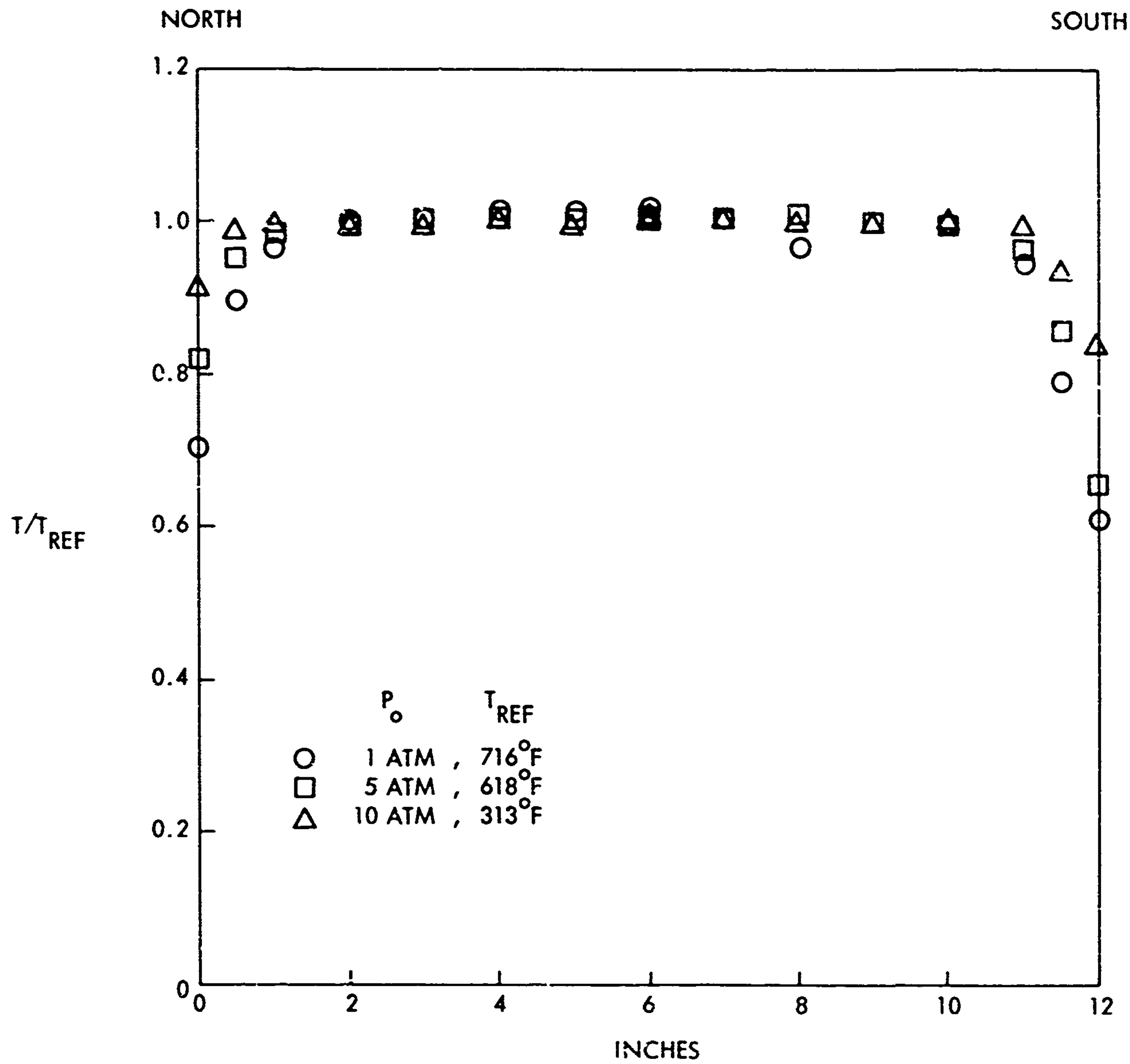

FIG.14 INLET TEMPERATURE PROFILE IN THE NORTH-SOUTH DIRECTION, X = -22".5

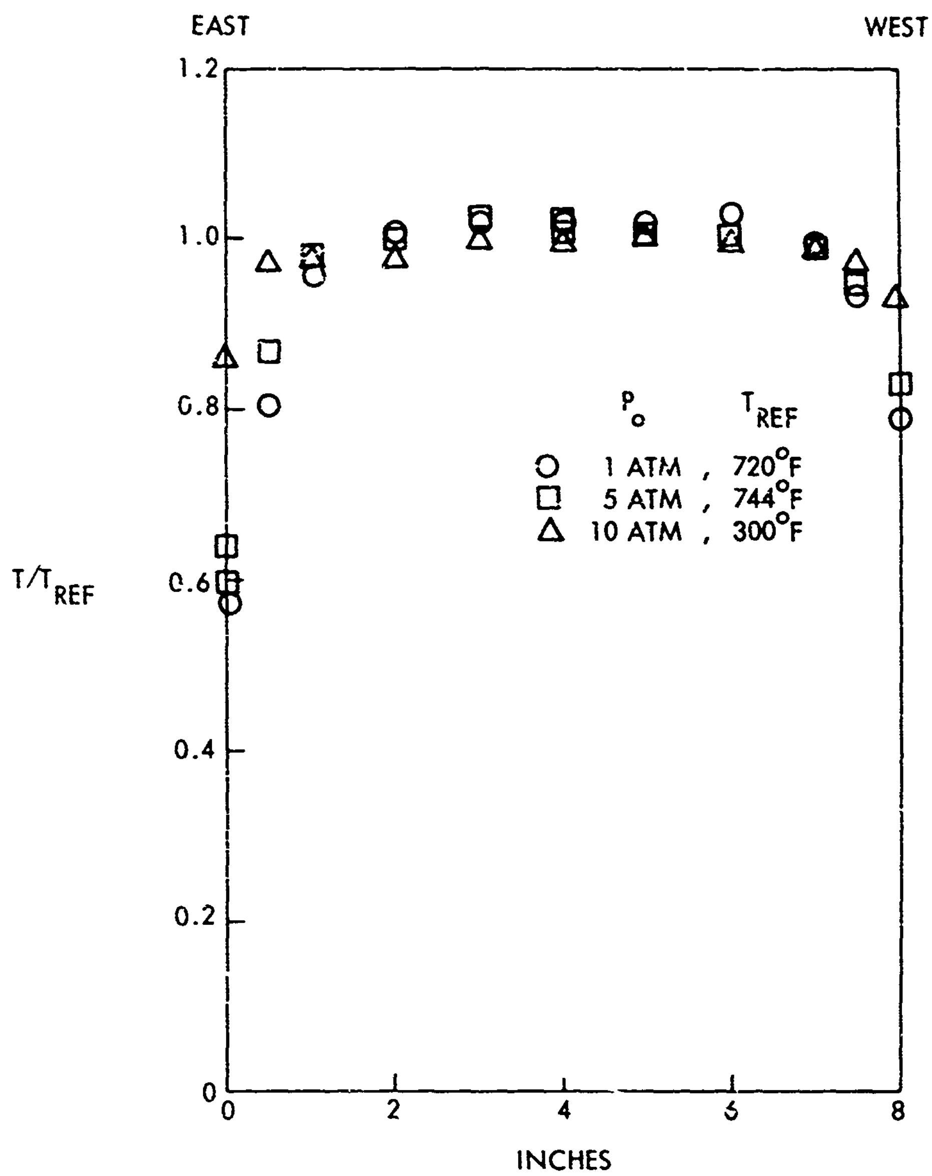

FIG. 15 INLET TEMPERATURE PROFILE IN THE EAST-WEST DIRECTION, X = -22"5

Figures 16, 17, and 18 are detailed free-stream calibration curves for the Mach 4.8 nozzle setting at 1, 5, and 10 atmosphere supply pressures, respectively. The Pitot pressures were measured with a five finger rake traversed in the axial direction with the probe heads in a plane 4 inches above the flat plate. The Pitot probes were 1.5 inches apart with the center probe traversing above the center line of the flat plate. The nozzle contour is designed to produce a zero pressure gradient flow on the flat plate beginning at 55 inches downstream from the nozzle throat when operated at 5 atmosphere supply pressure.

Figure 19 shows the static pressure distribution orifices located along the center line of the flat plate (circled points) on the flat plate 2.5 inches from the plate center line (squared points) and on the diverging side wall 3.56 inches above the flat plate.

Figure 20 is a comparison of the measured boundary layer thickness at one axial location with the previously described computation for turbulent boundary layer thickness. The agreement between the measured and computed boundary layer thickness on the flat plate side of the nozzle is within 5 percent. The edge of the boundary layer was experimentally defined as the location where the Pitot pressure reaches a plateau when surveyed across the boundary layer. A typical Mach number profile through the boundary layer is shown in figure 21.

The efficiency of the diffuser was investigated for the Mach 5 setting and at supply pressures of 1 and 4 atmospheres. The results are shown in figures 22 and 23. At 1 atmosphere supply pressure the maximum pressure recovery is 79 percent of the Pitot pressure while at 4 atmosphere supply pressure, the recover is 96 percent. Since the boundary layer thickness in the channel is larger at lower operating supply pressures (see figures 7, 8, and 9), a larger diffuser throat opening is required at lower pressures and a lower pressure recovery results.

The computed Reynolds number simulation capability for the Mach numbers 5 and 3 flow conditions are shown in figures 24 and 25. These curves were determined from isentropic flow relations and the measured channel performances shown in figures 12 and 13.

Figure 26 is a graph of the computed momentum thickness Reynolds number capability for the Mach number 5 nozzle contour setting. The previously described laminar and turbulent boundary layer flow computational method was used. The laminar curves may be used to estimate where transition occurs on the plate.

SUMMARY

A description has been given of the mechanical arrangement and aerodynamic performance of the NOL Boundary Layer Channel. It was designed to investigate the development of boundary layers in the transitional and turbulent regimes.

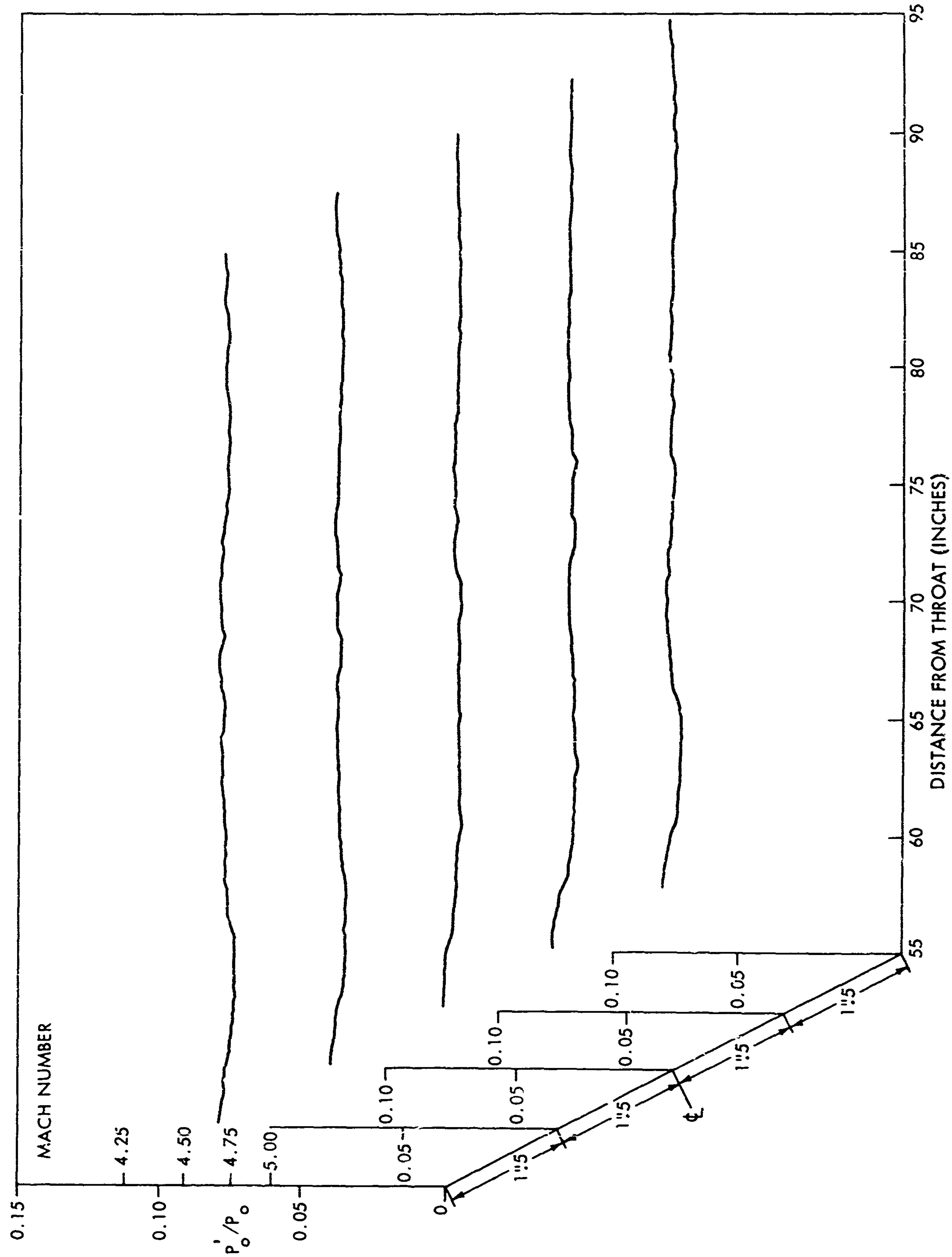

FIG. 16 AXIAL PITOT PRESSURE DISTRIBUTION, $P_o = 1$ ATM

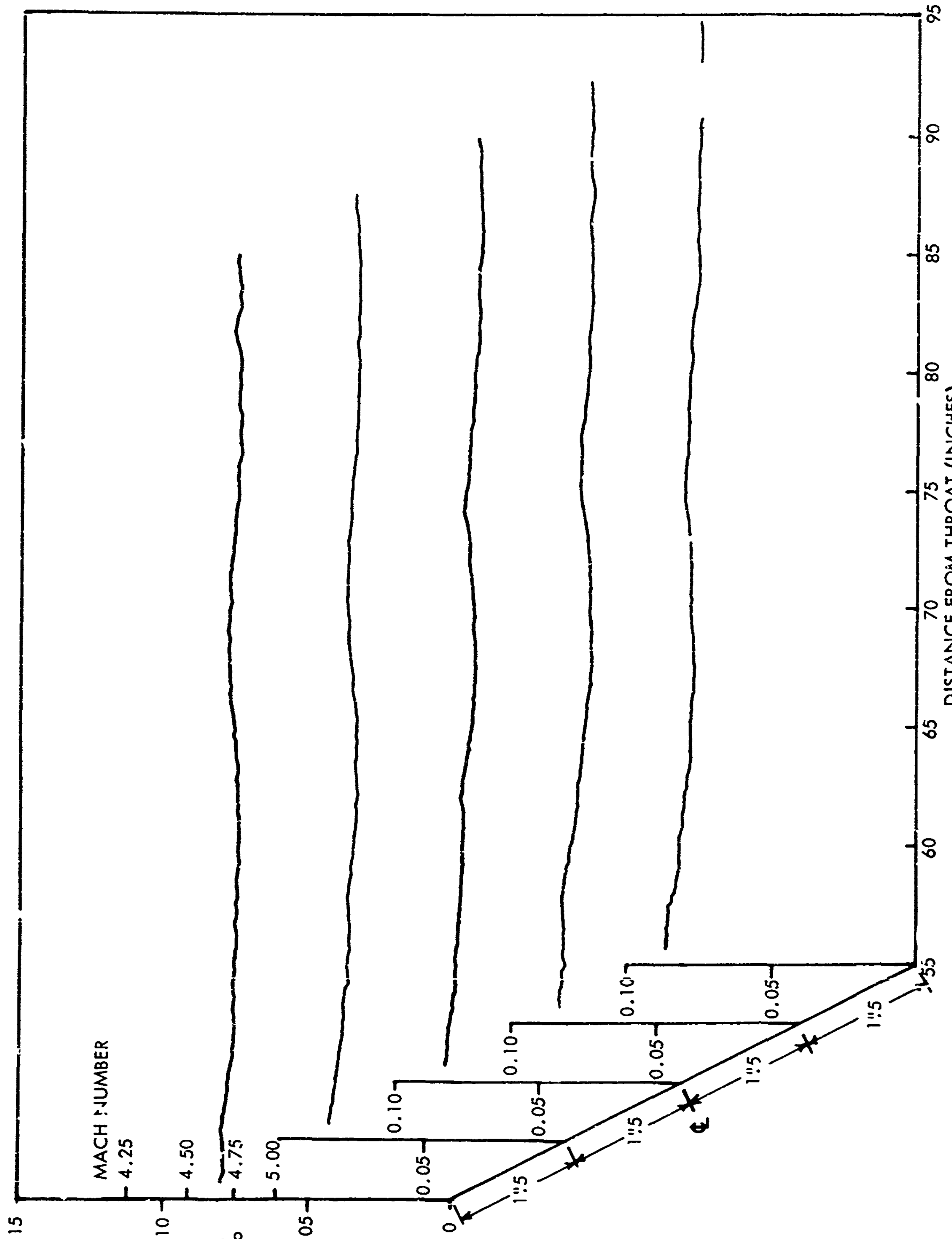

FIG.17 AXIAL PITOT PRESSURE DISTRIBUTION, P_o = 5 ATM

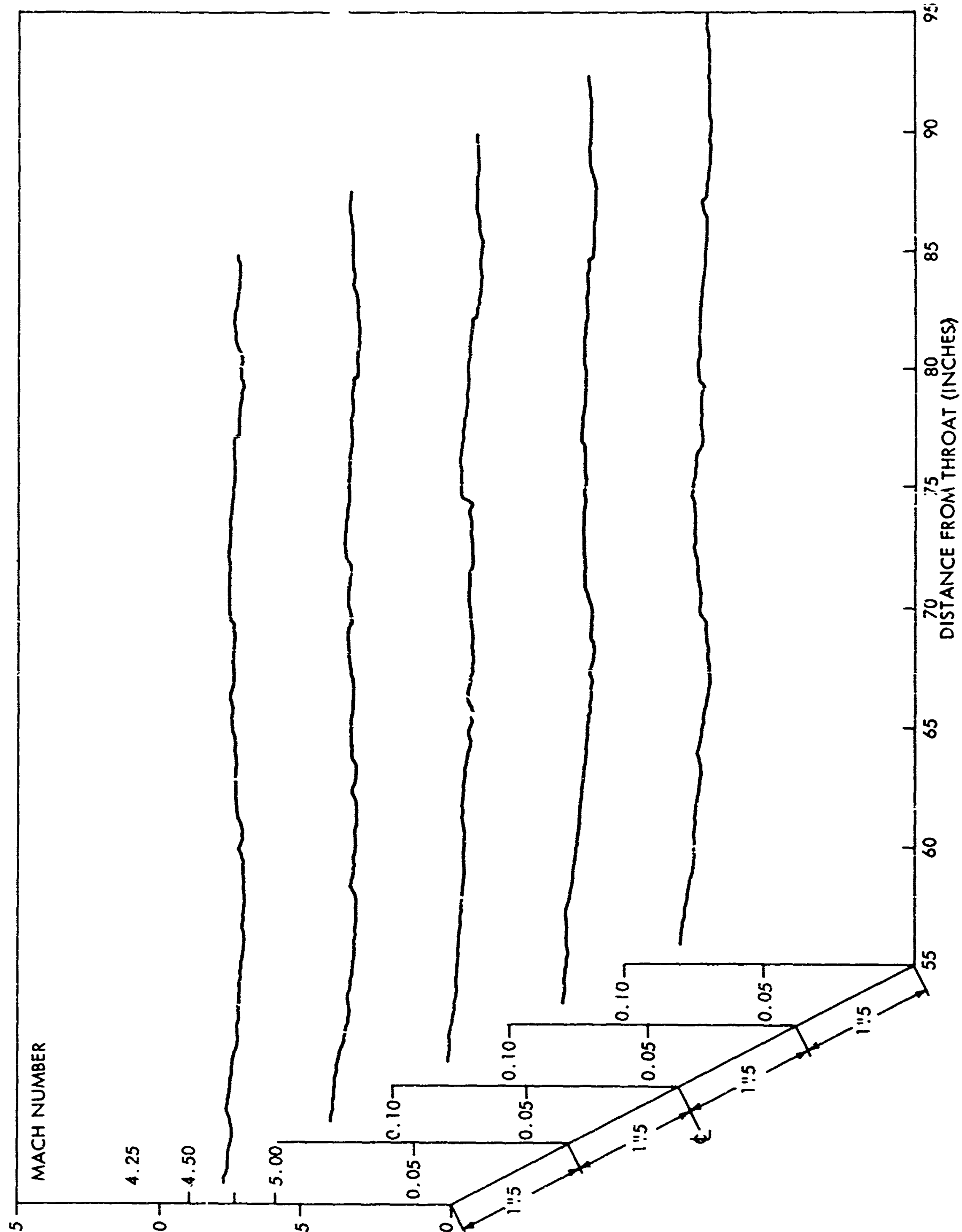

FIG. 18 AXIAL PITOT PRESSURE DISTRIBUTION, P_o = 10 ATM

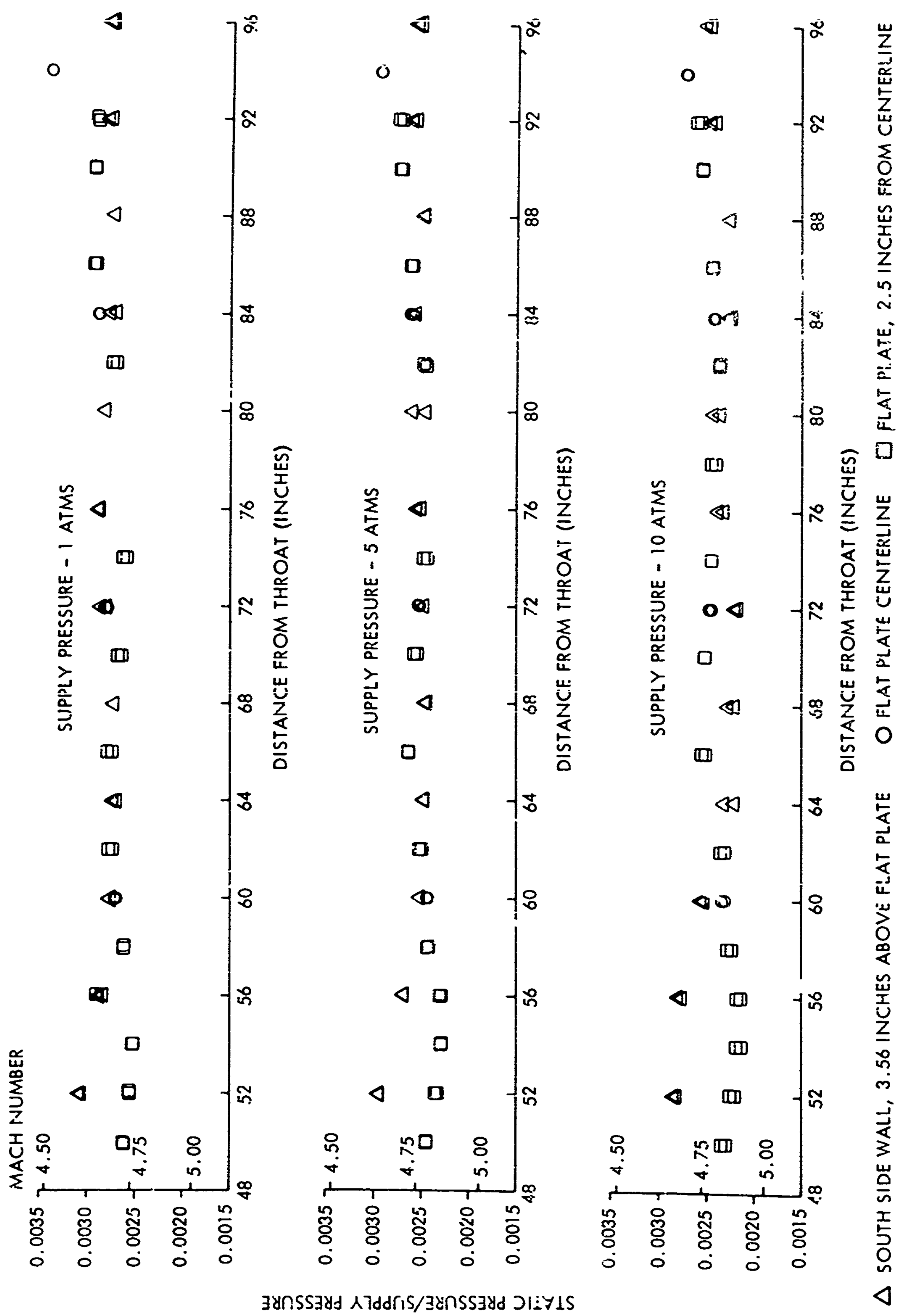

FIG.19 AXIAL STATIC PRESSURE DISTRIBUTION

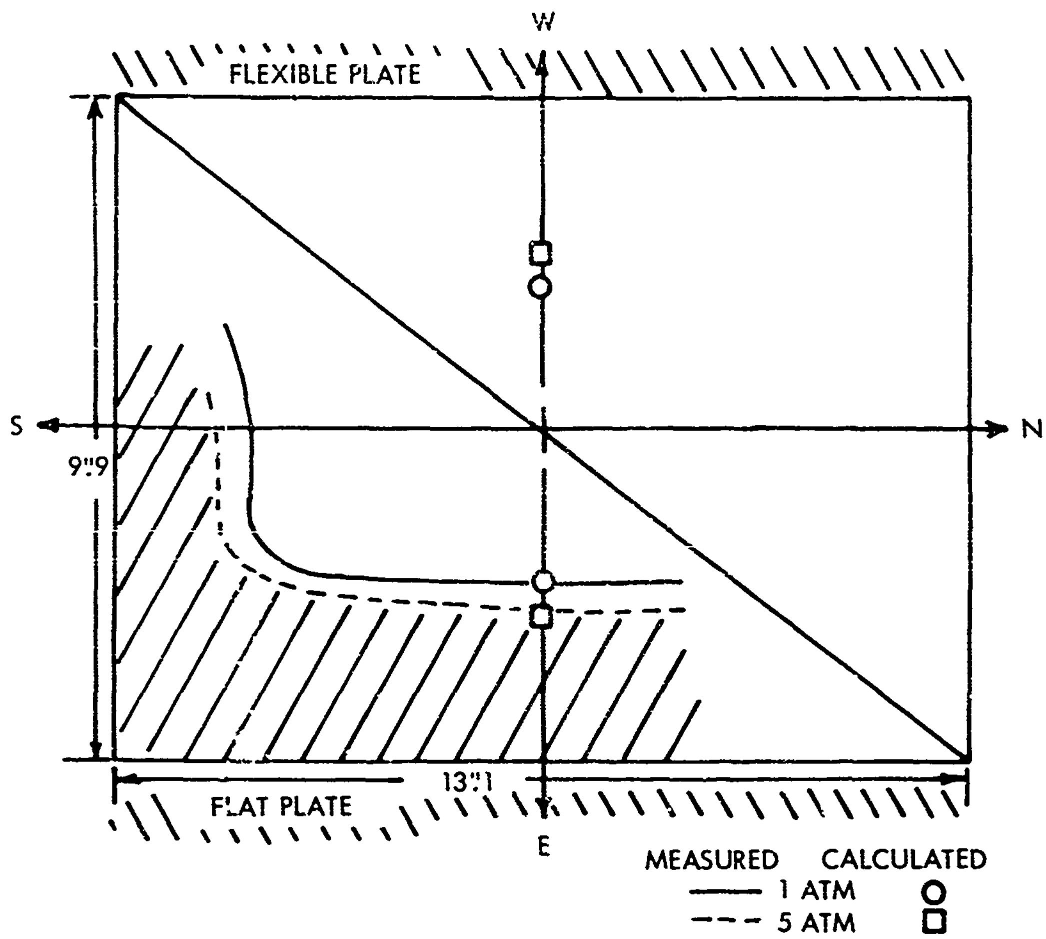

FIG.20 NOZZLE CROSS-SECTION SHOWING BOUNDARY LAYER FLOW DISTRIBUTION, MACH 5, X = 90"

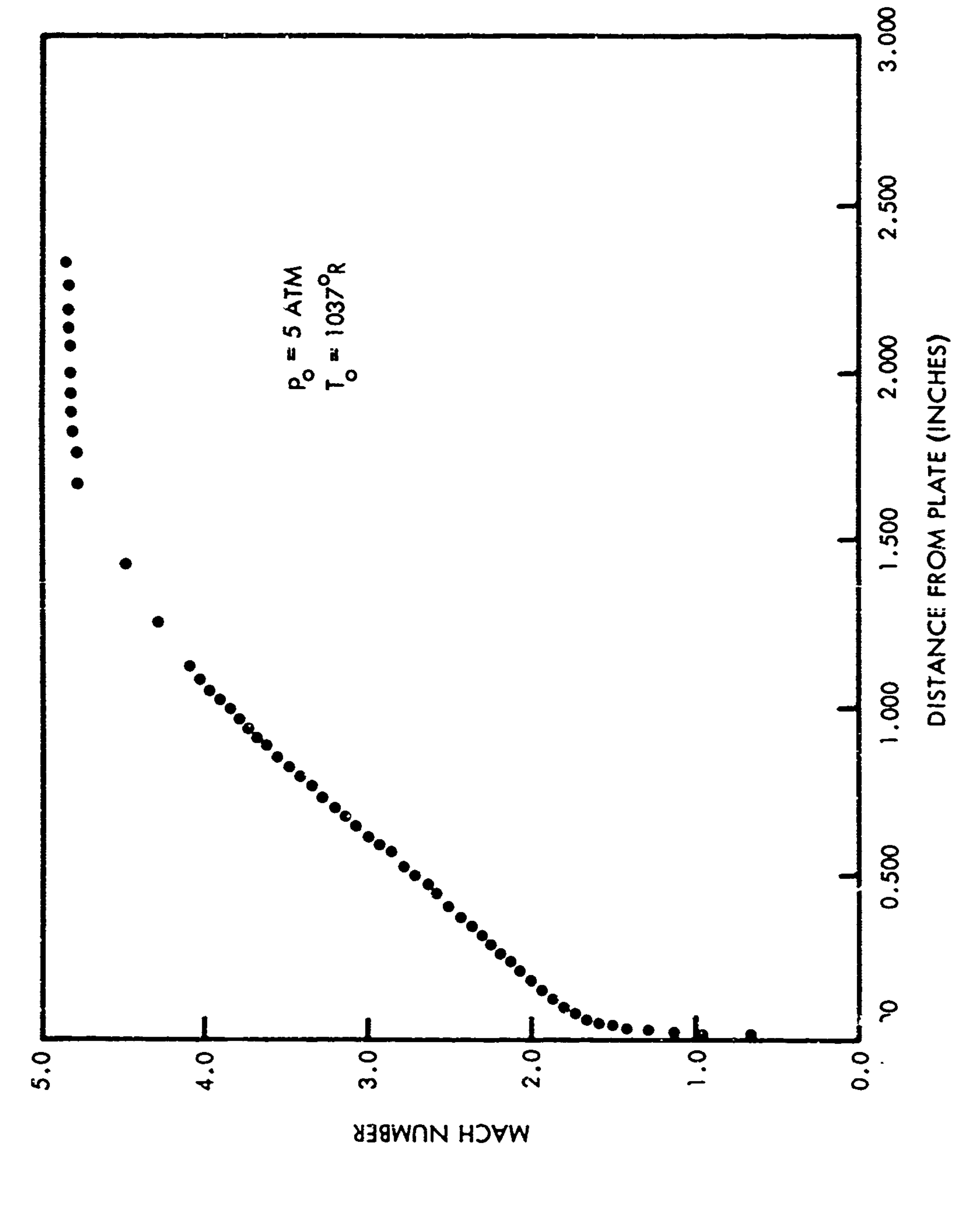

FIG. 21 EXPERIMENTAL MACH NUMBER BOUNDARY LAYER PROFILE, X = 70"

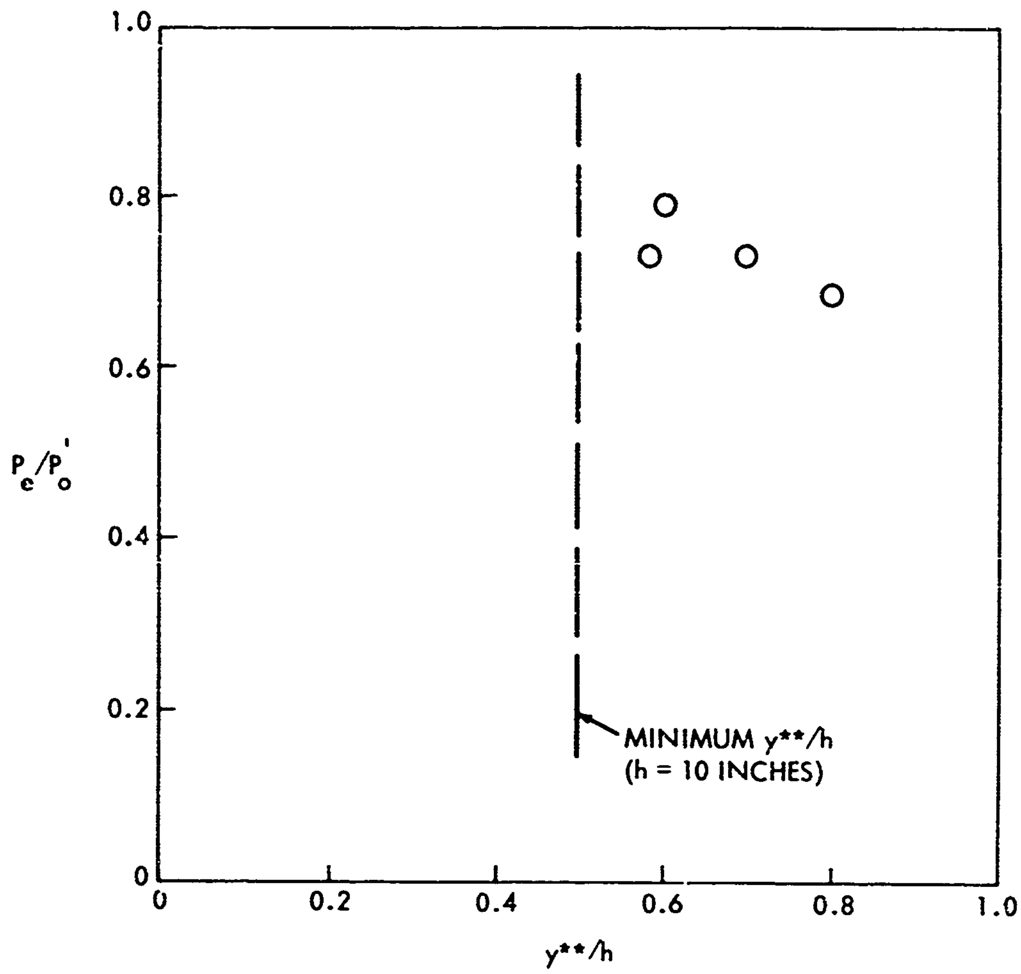

FIG.22 BOUNDARY LAYER CHANNEL DIFFUSER RECOVERY PRESSURE, P_o = 1 ATM

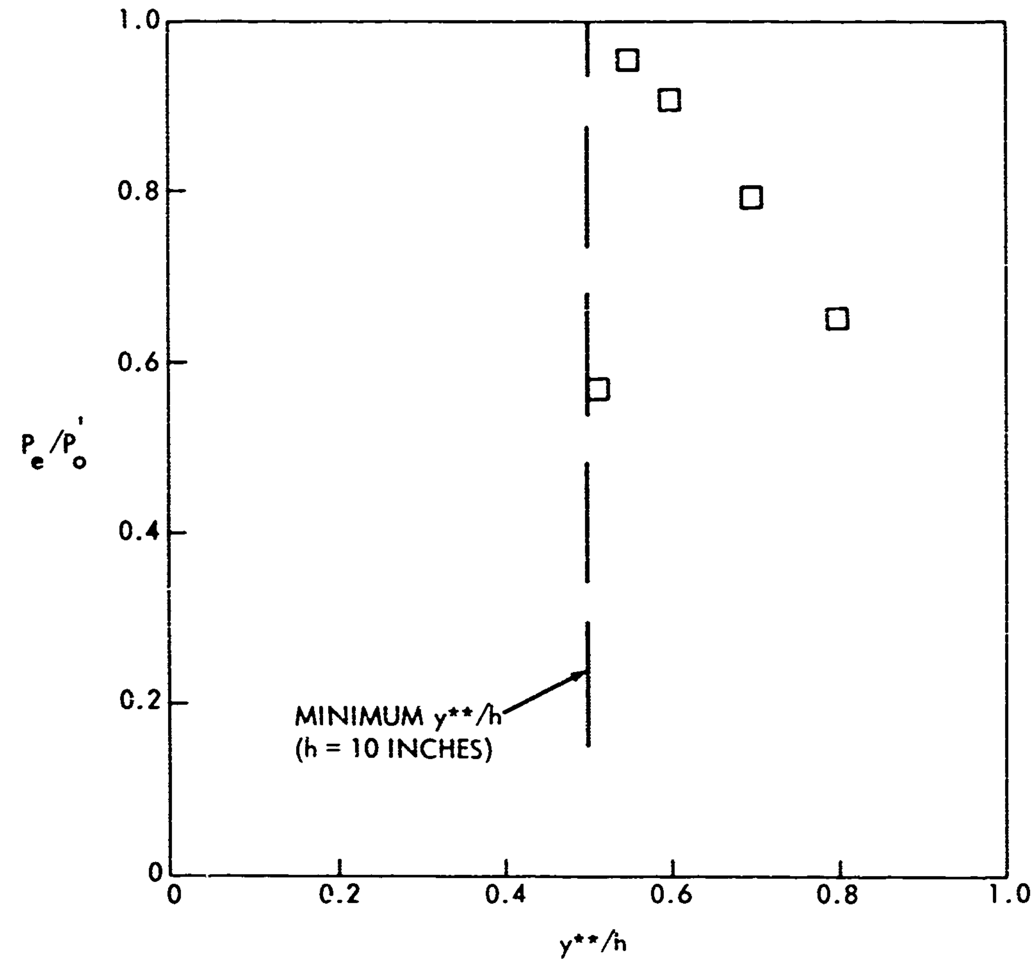

FIG. 23 BOUNDARY LAYER CHANNEL DIFFUSER RECOVERY PRESSURE, P_o = 4 ATM

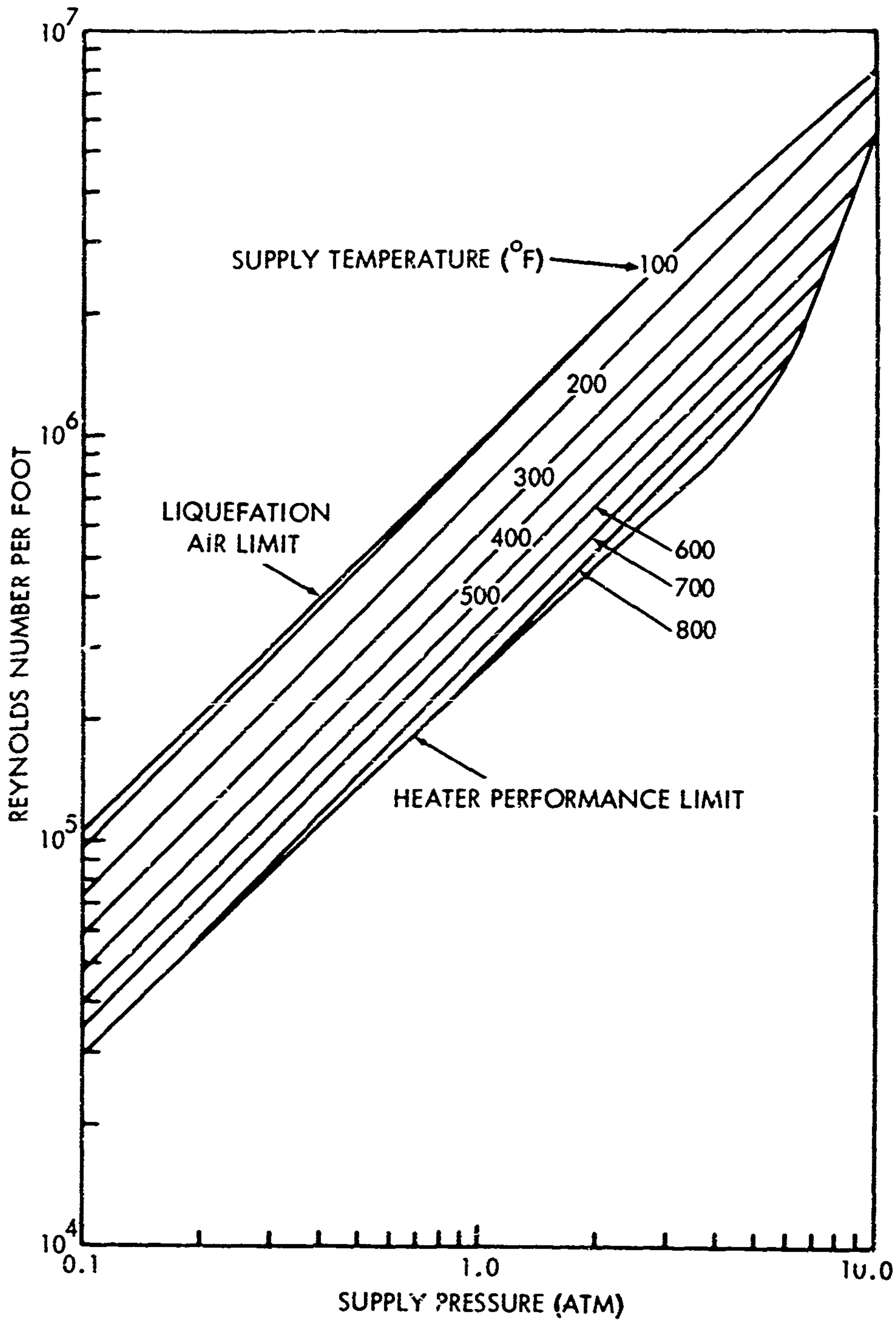

FIG.24 REYNOLDS NUMBER PER FOOT CAPABILITY, MACH 5

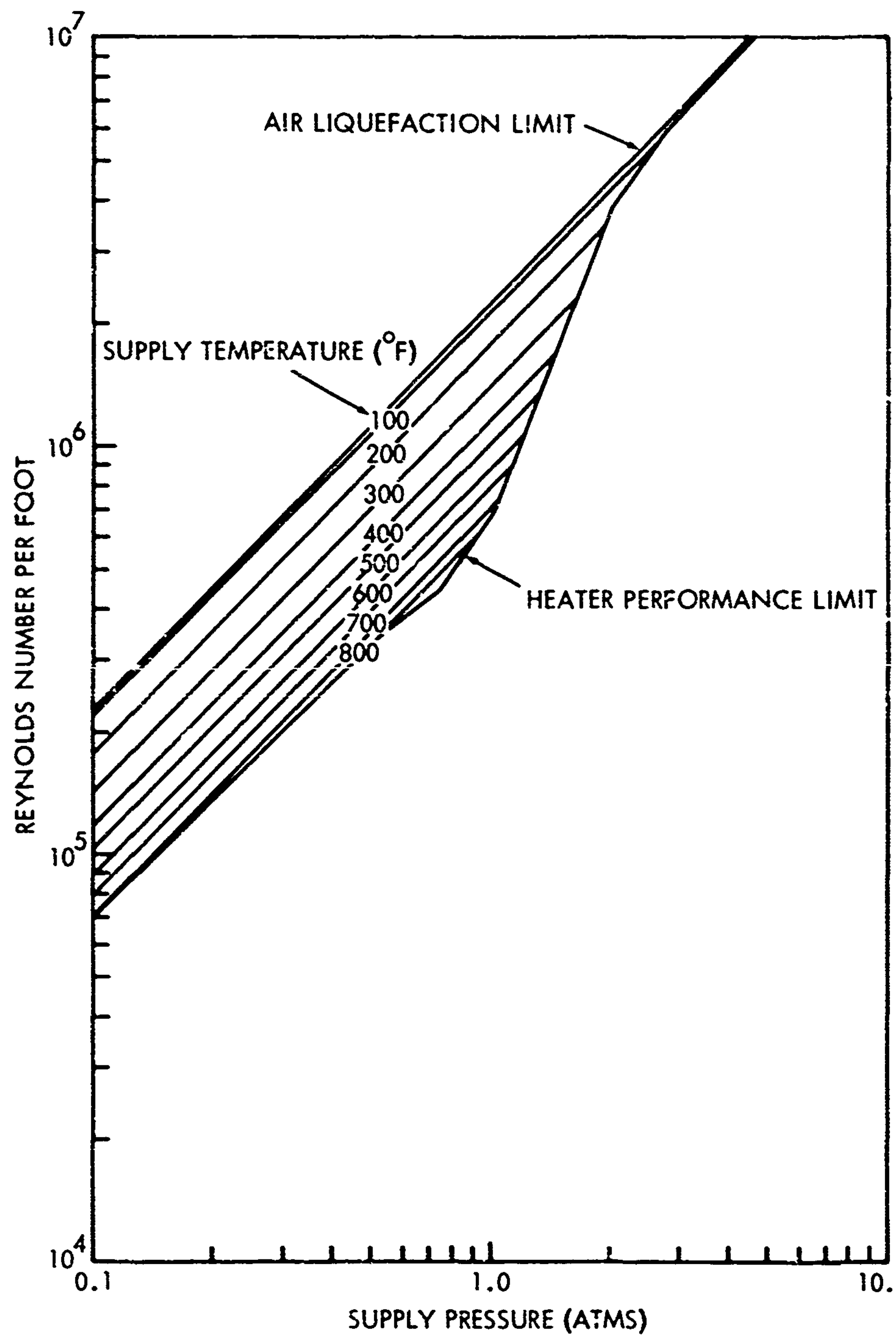

FIG.25 REYNOLDS NUMBER PER FOOT CAPABILITY, MACH 3

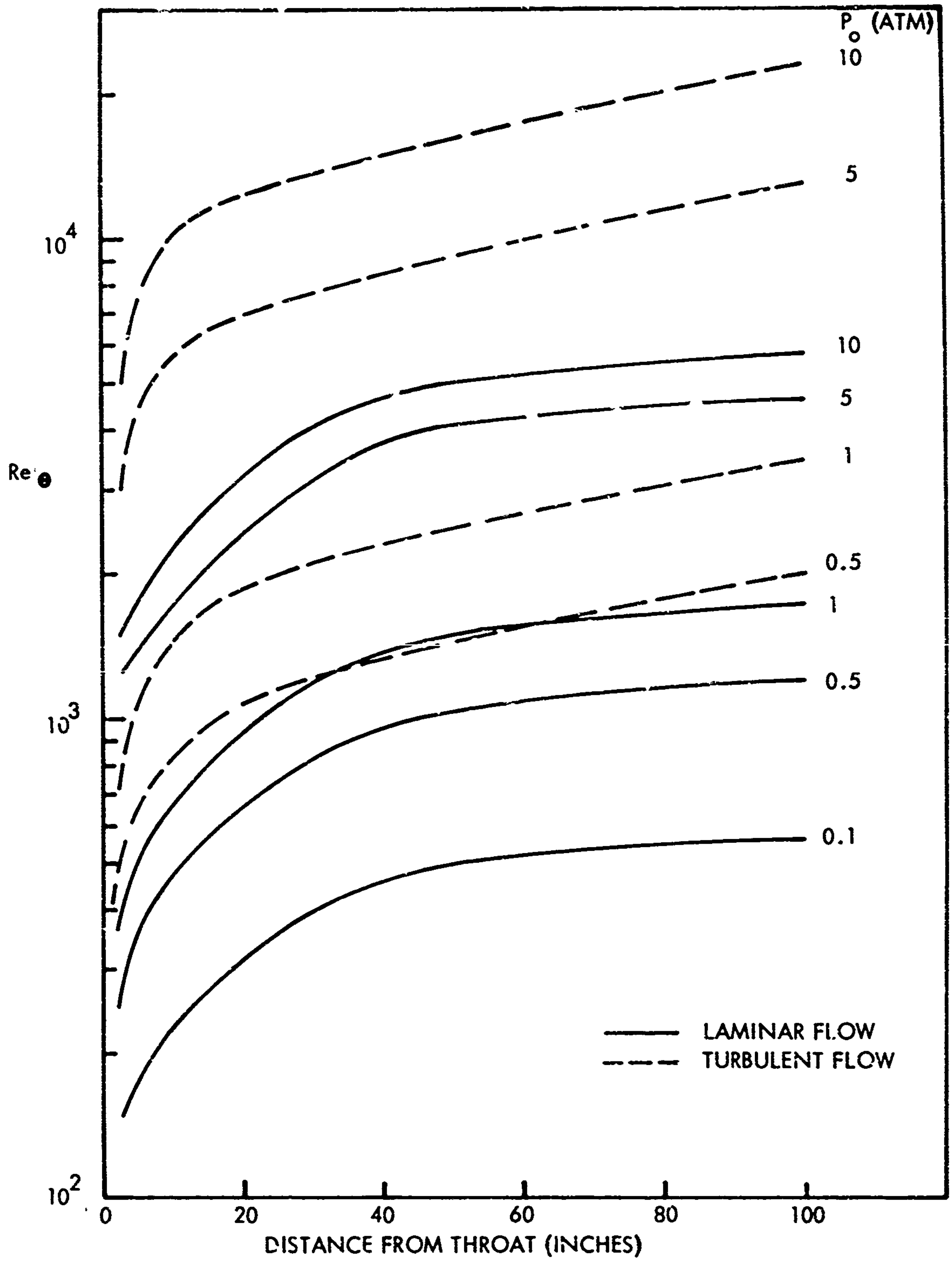

FIG. 26 CALCULATED MOMENTUM THICKNESS REYNOLDS NUMBER MACH 5

The channel consists of a variable contour, supersonic, half nozzle using a flexible plate and a system of jacks to prescribe the contour. The working model is a flat plate located on the opposite wall to that of the flexible plate. Instrumentation includes temperature probes, pressure probes, hot wire probes, and a direct skin friction balance.

The channel can be operated at Mach numbers from 3 to 7; supply temperatures up to 1000°F; and supply pressures from 0.1 to 10 atmospheres. Entrance funnels and throat sections have been fabricated for nozzles having nominal exit Mach numbers of 3 and 5. At the present time the channel has only been operated in the Mach 5 mode. The Reynolds number per foot capability at Mach 3 is 10^5 to 2.4×10^7 and at Mach 5 is 3×10^4 to 8×10^6.

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13 ABSTRACT

A Mach 3 to 7 blow-down wind tunnel facility for investigating boundary layer phenomena in the transitional and turbulent range is described. The facility, referred to as the Boundary Layer Channel, utilizes a flexible plate and a flat plate to form the two opposite walls of a two-dimensional supersonic nozzle. The plate is 8 feet long. The channel operates at supply temperatures up to 1000°F and supply pressures from 0.1 to 10 atmospheres. The Reynolds number per foot capability is from 3×10^4 to 2.4×10^7.

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