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HYPERVELOCITY WIND TUNNEL NUMBER 9 HIGH MACH NUMBER DEVELOPMENT PROGRAM

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FOREWORD

This report documents the High Mach Number Development Program conducted in the Hypervelocity Wind Tunnel Number 9 (Tunnel 9) located at the White Oak, Maryland site of the Dahlgren Division, Naval Surface Warfare Center. The National Aerospace Plane Joint Program Office (NASP JPO) was the project co-sponsor. The primary objective of this program was to investigate the possibility of simply and inexpensively modifying Tunnel 9 to operate at higher Mach numbers.

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ABSTRACT

This report describes the results of the High Mach Number Development Program performed at the White Oak, Maryland site of the Dahlgren Division, Naval Surface Warfare Center. The goal of this program was to expand the capabilities of the Hypervelocity Wind Tunnel Number 9 (Tunnel 9) to include operation at Mach 18. The constraints of this program involved using the existing Mach 14 setup with as little modification as necessary.

There were two major areas of interest for this program, the heater and the nozzle. The required supply temperature for Mach 18 operation is above the current capabilities of the Tunnel 9 Mach 14 heater. Utilizing supercooled flow conditions lowered the required supply temperature to within the Mach 14 heater capability. The current Mach 14 nozzle was used and the throat section was replaced with a new hardware set designed to achieve the correct nozzle throat-to-exit area ratio to obtain the higher Mach number.

Forty-one runs were carried out in Tunnel 9 in support of this program. The Mach number capability in Tunnel 9 has been extended to Mach 16.5. For this condition the flow has a 30-inch test core with Pitot pressure deviations of -1.1 percent to +1.3 percent and 3.5 seconds of good run time. A Mach 18 capability has also been investigated. Research efforts to achieve acceptable Mach 18 conditions are continuing.

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INTRODUCTION

This report documents the High Mach Number Development Program conducted in the Hypervelocity Wind Tunnel Number 9 (Tunnel 9) located at the White Oak, Maryland site of the Dahlgren Division, Naval Surface Warfare Center. The National Aerospace Plane Joint Program Office (NASP JPO) at Wright Patterson Air Force Base co-sponsored the program.

It has been recognized that there is a need for high Mach number facilities to support NASP and other hypersonic programs. The purpose of this study was to determine if Tunnel 9 could be simply and inexpensively modified to operate at higher Mach numbers. The goal of this development program was to achieve Mach 18 flow.

Critical components of any hypersonic wind tunnel are the heater and nozzle. The heater must heat the gas sufficiently to avoid the presence of condensate in the flow as the flow accelerates and expands through the nozzle. The required supply temperature for Mach 18 operation is above the current capability of the Tunnel 9 Mach 14 heater. Thus, the first objective was to determine if the use of supercooling could lower the supply temperature requirements to within the current heater capabilities and produce valid aerodynamic results. This would eliminate the need for a redesign of the heater package.

The second objective of this program was to avoid the manufacture of a new nozzle by replacing the existing Mach 14 nozzle throat section with a new hardware set designed to achieve the correct nozzle throat-to-exit area ratio. Tunnel 9 uses interchangeable contoured nozzles that can cost upwards of one million dollars. With a cost of approximately 30 thousand dollars, nozzle throat inserts are more cost effective. Testing was required to determine if the flow was of sufficient quality to support aerodynamic testing.

FACILITY DESCRIPTION

All testing was conducted in the Navy's Hypervelocity Wind Tunnel No. 9. This is a blow-down type facility that uses nitrogen as the working fluid. The use of three interchangeable contoured nozzles allows for testing at Mach numbers of 8, 10 and 14, with maximum Reynolds numbers of approximately 52 million per foot, 20 million per foot and 4 million per foot, respectively. For Mach numbers of 10 and 14 the nozzle exit and test cell are five feet in diameter. The Mach 8 configuration has a nozzle exit diameter of 33 inches and a test cell diameter of five feet. This test section can accommodate large hypersonic test models. Figure 1 is a schematic of the facility.

Before the run, nitrogen is pumped into a set of three driver vessels. During this pumping cycle, the test cell, nozzle diffuser and vacuum sphere are evacuated to a pressure of approximately 1 mmHg. The heater vessel is pressurized with a fixed quantity of gas from the driver vessel. This gas is then heated to the required tunnel supply temperature.

Two metal diaphragms upstream of the throat separate the high temperature, high pressure gas in the heater from the evacuated nozzle and the test cell region. A tunnel run is initiated by bleeding high pressure gas from the driver vessels into the region between the diaphragms, causing the downstream diaphragm to burst. A large pressure differential then causes the upstream diaphragm to burst, causing the flow to start. As the hot gas flows out of the top of the heater, relatively cold high pressure gas from the driver vessels enters the bottom of the heater vessel. This cooler gas acts as a fluid piston to maintain steady supply conditions. The run ends and the tunnel shuts down after the fixed volume of working fluid is exhausted and the supply temperature and pressure begin to decrease. For detailed information concerning Tunnel 9 operation, see Reference 1.

TEST PHILOSOPHY

Development efforts were carried out for Mach numbers of 16.5 and 18. Modifications to two primary tunnel components, the heater and the Mach 14 nozzle, were required to carry out this program. The following sections will discuss each of these separately.

TUNNEL 9 HEATER AND SUPERCOOLING

Currently, the Tunnel 9 Mach 14 heater has an upper operating limit of 3700° R. The required supply temperature for Mach 18 operation is 4300°R. To make use of the Mach 14 heater, the phenomenon of supercooling was used to lower the required supply temperature. Supercooling refers to the existence of a nonequilibrium pure phase state with the physical properties of a different equilibrium phase at a lower temperature. This phenomenon has been investigated and documented for both large and small hypersonic nozzles.[2] For this paper, degrees supercooling are defined as the number of degrees the calculated perfect gas free-stream temperature is below the equilibrium saturation temperature, calculated from the Clausius-Clapeyron Equation (1), at a given pressure.

$$\ln (P * 6893.25) - 22.527 = \frac{-1486.8}{T} \tag{1}$$

Supercooling can have a significant role in the development of hypersonic facilities. Reducing the required free-stream temperature also reduces the required supply temperature. Equation 2 shows the relationship between free-stream temperature and supply temperature.

$$\frac{T}{T_o} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{-1} \tag{2}$$

For example, at Mach 18, for each 1° R of supercooling used, the required supply temperature is reduced by 66°R. Thus, by incorporating 15°R of supercooling, the required supply temperature is reduced to 3310° R which is within the operating limits of the existing Tunnel 9 heater.

A comprehensive program has been carried out to explore the phenomenon of supercooling. Calibration models and cone models have been tested in condensation-free supercooled flow at Mach 14 in Tunnel 9 and at Mach 18 in Tunnel 8A. References 3 - 6 discuss these studies. Results from these tests revealed that the test cell flow in Tunnel 9 does not condense until over 48°R of supercooling has been used and that valid aerodynamic data can be obtained with up to 25°R of supercooling.

Figure 2 shows a compilation of data obtained in supercooling studies at NSWCDD. The line to the far right represents the sublimation (or saturation) line for nitrogen as defined by Equation 1. The line labeled "experimental condensation onset curve" is a boundary observed in studies performed by Daum and Gyarmathy in which the supercooling phenomenon was observed in a variety of wind tunnels.[2] There are two types of data shown in the plot. Those points that are labeled as "OPER PTS" represent the actual free-stream values obtained in Tunnel 9 operation at the condition indicated. The remaining data points represent the states of condensation onset or disappearance as observed in NSWCDD wind tunnels. The figure shows that the Mach 16.5 and Mach 18 operating points do not reach the boundary expressed by the onset and disappearance of condensation. These points are in the supercooled region.

MACH 14 NOZZLE MODIFICATIONS

Tunnel 9 uses large axisymmetric contoured nozzles. For Mach 14 operation, the nozzle is 40 feet long with a throat diameter of 1 inch and an exit diameter of 60 inches. Rather than design and fabricate an entirely new higher Mach number nozzle, three sections in the throat region of the existing Mach 14 nozzle were replaced. Figure 3 shows the first 3 feet of the existing Mach 14 nozzle and a superimposed outline of a new higher Mach number contour (the inner contour). In this figure, the replaced sections are the subsonic inlet section, the throat section and the screwed insert which are labeled 1, 2 and 3, respectively. The throat section was redesigned to yield Mach 18 flow at the fixed nozzle exit diameter of five feet. The new parts were smoothly contoured into the existing nozzle hardware by matching the first and second derivatives of the contour coordinates. The design throat diameter for Mach 18 operation is 0.525 inches. Later in the program a Mach 18 throat was modified to produce Mach 16.5 flow. The design throat diameter for Mach 16.5 operation is 0.628 inches.

NOZZLE THROAT HARDWARE

Six sets of Mach 18 throat hardware were manufactured. Drawings and contour coordinates for each piece, as designed, are shown in Figures 4 - 6. Hardware set 1 was manufactured by Smackover, Inc. Sets 2 through 6 were manufactured by B-J Enterprises, Inc. The as-built minimum throat diameter for each hardware set is listed in Table 1.

To observe the effect of contour changes on the test cell flow profile, dimensional analyses were performed following each run. Typically, during the first few runs in Tunnel 9 a new throat will decrease in diameter. The operating temperatures are high enough to cause the material to expand. The throat hardware is constrained such that it must expand inward toward the centerline. Thus, by expanding, the throat decreases radially. After the eighth run on hardware set 1, the dimensional changes were within the measurement error (± 0.003 inches) and no additional measurements were taken. The final minimum throat diameter was 0.4959 inches representing a decrease of 0.0303 inches in throat diameter. Figures 7 - 9 are graphs showing the contour of the as-built hardware and the contour after eight runs. From calibration data it was determined that the dimensional changes in the throat do not appreciably affect the flow field. Figure 10 shows non-dimensional pressure data from the traversing rake for runs with the original throat contour and the contour after 12 runs.

Later in the program, the throat piece of hardware set 3 was modified to lower the resulting free-stream Mach number to 16.5. The modification, which involved drilling a constant area cylindrical section out of the throat region, was performed in-house. Figure 11 is a graph showing the contour of throat 3 following the modification.

When originally received, hardware set 6 did not meet specifications and was returned to the manufacturer for remachining. This hardware was machined with a new oversized contour. This oversized contour was designed to account for radial changes experienced during the first runs on a new throat. Details on this contour are provided in Reference 7.

HARDWARE AND INSTRUMENTATION

TUNNEL INSTRUMENTATION

Measured tunnel conditions are supply pressure, supply temperature and Pitot pressure. Supply pressure is measured with a Viatran 214 transducer with a range of 0 - 50,000 psia. Supply temperature is measured using two tungsten-5 percent rhenium/tungsten-26 percent rhenium thermocouples, each with a range of 0 - 4200°F. Values from both thermocouples are averaged. When using the 25 probe calibration rake, two of the probes located in the core region (one on each side of the centerline) are averaged to obtain Pitot pressure measurements. When the cone model was installed, two strut mounted Pitot probes, installed 18 inches from the tunnel wall, were used. A schematic of the test cell is shown in Figure 12.

CALIBRATION RAKE

To perform the flow calibrations, a 25-Pitot probe, fixed rake was installed horizontally in the test cell and positioned at various axial locations downstream of the nozzle exit plane. The Pitot probes are spaced 2 inches apart. Pressure measurements were made using Kulite XCW-093-15A gages.[1] These are miniature, fast response transducers. Temperature compensation was provided to avoid any possible drift of gage readings due to calibration rake heating. An excitation voltage of 10 Volts was maintained and monitored throughout the program. A photograph of the calibration rake is shown in Figure 13.

VERTICALLY TRAVERSING RAKE

A vertically traversing rake was configured with 3 Pitot probes spaced 1 inch apart, horizontally. For all runs in this series the traverse was mounted on top of the tunnel at window station one. The probes were located 12 inches downstream of the nozzle exit plane as shown in Figures 12 and 13. Data from the probes was used to compare the repeatability between runs. The traverse had various paths of travel that were run dependent. Typically the probe traversed from 4 inches above the centerline upward to a location approximately 2 inches from the tunnel wall. Pitot pressure measurements were made with Kulite XCW-093-15A gages.[1]

CONE MODEL

Previous supercooling studies indicated that a blunt-nosed body is more sensitive to the effects of supercooling than a sharp nosed body.[5] To obtain data on an aerodynamic configuration, a blunt-nosed 7° half-angle cone was used. The cone has a length of 47 inches, a base diameter of 14.4 inches and a bluntness ratio of 22.31 percent. The model was placed in window station 1 such that the nose of the cone was positioned 24 inches downstream of the nozzle exit plane. Instrumentation consisted of the 9HV6-5 force balance, 24 PTQH 0-5 psia transducers and 21 coaxial thermocouples. The force balance is a force-force balance manufactured by the Abel Corporation.[1] Maximum load capabilities are as follows: 2000 lb. in normal force, 1000 lb. in yaw force, 600 lb. in axial force and 800 in-lb. in rolling moment. PTQH pressure transducers are solid state gages with good linearity for pressures as low as 10 microns.[1] The thermocouples are commercially available surface temperature gages from Medtherm Corporation. Heat transfer rates were calculated using the one-dimensional heat conduction equation for a planar slab.[1] The instrumentation layout is shown in Figure 14.

OPTICAL DIAGNOSTICS

To monitor the presence of condensation, an optical system to detect back-scattered laser light from condensation particles was implemented. This system has been used successfully in previous Tunnel 9 testing[3] and consisted of a 3 mW Helium-Neon laser, a photomultiplier and collecting optics. A schematic of this system is shown in Figure 15.

NOZZLE THERMOCOUPLES

The nozzle wall was instrumented with six coaxial thermocouples to measure wall heating and ascertain the boundary-layer state. All gages are located on the left side (facing upstream) of the nozzle. Thermocouple locations are shown as axial distances from the throat in Figure 16.

DIFFUSER PROBES

Three cone-static probes were installed in the diffuser pipe to determine the Mach number and static pressure of the flow in this region. The axial locations are shown in Figure 17.

MICROTUFTS

Fluorescent microtufts were added to the tunnel wall to provide flow visualization in the wall boundary-layer region. Nylon monofilament material was dyed with Leucophor EFR that fluoresces when excited by ultraviolet light. Since the fluorescence is in the visible spectrum, images can be captured on standard photographic film. Tufts were applied on the tunnel wall in a matrix consisting of 20 rows and 31 columns. The tufts were cut horizontally into 1 inch segments with 1 inch vertical spacing. Four exposures were obtained during the run at times 0.8, 0.9, 1.2 and 1.4 seconds after the tunnel start-up. Additional information on the microtuft procedure for Tunnel 9 is contained in Reference 8.

BOUNDARY LAYER RAKES

Two boundary layer rakes were installed in the test cell. The first rake was positioned in window station one. The rake is 6 inches long and contains 8 Pitot probes as shown in Figure 18. The second rake, positioned in window station three, is 22 inches in length with 14 Pitot probes as shown in Figure 19. Pitot pressure measurements were made using Kulite XCW-093-15A gages.[1] The orientation of all rake and strut mounted instrumentation is shown in Figure 20.

DATA ACQUISITION

Data were obtained with the Data Acquisition and Recording Equipment (DARE) VI. DARE VI is a simultaneous-sample-and-hold, single amplifier per channel system with 14 bit resolution. The output signals from all of the instrumentation were amplified and fed through 25 Hz, lowpass, analog, six-pole Bessel filters. Data were recorded on each channel at 250 samples per second.

Pressure transducers were calibrated prior to each run. The transducers were compared to MKS Baratron reference transducers that monitor the test cell pressure. During the vacuum pumpdown sequence, the pressure was held constant momentarily at suitable levels to allow for data recording. The interval between the conclusion of the pumpdown sequence and the actual run was up to 20 minutes in length. A final tare reading was taken just prior to the run to correct for any zero shift that may have occurred during this time. A linear least squares method was used to calculate a slope and an intercept for each transducer.

DATA REDUCTION

All data were reduced using standard NSWCDD codes. In addition to the 25 Hz analog filters used during data acquisition, the data were filtered with lowpass sixth order Butterworth digital filters during data reduction. The cutoff frequency was 10 Hz for all data channels excluding balance gage channels. The cutoff frequencies for balance gage channels are as follows:

Normal Force	5 Hz	Pitching Moment	5 Hz
Side Force	3 Hz	Yawing Moment	3 Hz
Axial Force	5 Hz	Rolling Moment	3 Hz

An estimate of the uncertainties involved in measuring Tunnel 9 flow parameters was previously conducted.[9] The measured and derived properties' uncertainties in terms of percentage errors are contained in Table 2.

EXPERIMENTAL RESULTS

To date, 41 runs have been made in support of this program. Additionally, four runs with hardware set 2 were made with a NASP 2-D inlet as part of the NASP JPO Government Work Package, GWP 43 (WTR 1609). A complete run matrix is given in Table 3.

Figure 21 shows a trace of the supply pressure and supply temperature for a typical Tunnel 9 run. There are approximately 3.5 seconds of good flow for each run. Figure 22 shows a typical trace of the photomultiplier signal. During the tunnel start-up, condensation is present causing the photomultiplier to output a large voltage signal. When steady flow conditions are established the condensation disappears, causing the strength of the signal to decrease and return to the prerun ambient level. When the run was near completion and the supply temperature decreased, condensation was again present and the signal returned. At Mach 16.5 and Mach 18 conditions the run time and shutdown process are relatively long. Since data was only acquired for six seconds, the onset of condensation at the end of the run is not visible in the data trace. However, this event was verified using an oscilloscope. All of the runs in this test series were condensation-free (in the test cell) during steady flow.

RESULTS WITH ORIGINAL MACH 18 THROAT HARDWARE

The first series of runs (2271 - 2276) were made with hardware set 1. The distribution of normalized Pitot pressure across the test core for run 2274 is shown in Figure 23. Pressures were normalized with the average of the pitot pressures located ± 8 inches from the centerline. Tabulated data for this run are shown in Table 4. All data were averaged over the useful run time. The core was approximately 24 inches, but due to the resolution of the Pitot probes, the border between the boundary layer and the core can only be determined within ± 2 inches. The Pitot pressure is 4.94 psia with a variation of -3.4 percent to +2.1 percent. These results are consistent with the results from the Mach 14 calibrations at a Reynolds number of 2.03×10^6 per foot (see Reference 10).

Near the end of run 2274 the sheath of a supply thermocouple melted causing damage to the throat insert of hardware set 1. In an attempt to repair the damage, the throat hardware was returned to the manufacturer for remachining. Since the throat diameter had decreased, when material was removed from the throat to repair the damage, the throat was returned to its original diameter. The second series of runs (2293 - 2295) were made with hardware set 1 after the throat piece had been remachined. It was hoped that after the hardware had been refurbished it would produce results similar to those from the initial runs. However, residual stresses locked in the material altered the expansion characteristics of the material and the data profile was drastically altered by the throat damage and hardware remachining. The core size was reduced from 24 inches to 20 inches and the flow character was more asymmetric. The Pitot pressure deviations had increased to -6.2 percent to +1.5 percent. This set of throat hardware was determined to no longer be suitable for testing and has since been taken out of service.

The purpose of the next series of runs (2299 to 2309) was to address facility issues associated with higher Mach number operation of Tunnel 9. Before a Mach 18 upgrade could be put fully into a production capability, some questions concerning the endurance of tunnel hardware needed to be addressed. Since the Mach 18 throat diameter is only 1/2 the diameter of the Mach 14 throat, the mass flow is decreased by a factor of four. With this reduced mass flow and increased run time, the heat soak on the facility hardware is much more severe. The exposure of parts to extreme temperature for four times longer has resulted in diminished hardware lifetimes.

RESULTS WITH MACH 18 THROAT HARDWARE SET 2

Results from the initial series of runs suggested continuation of this project. Since the original throat had to be taken out of service, testing continued using a new set of throat hardware. Hardware set 2 was first tested during runs 2338 - 2341 on a NASP 2-D inlet. Due to the presence of the test model, the calibration rake could not be installed. The vertically traversing rake was operated for each of these runs and flow profiles were obtained. Run 2338 has a test core of 30 inches and a Pitot pressure of 4.008 psia with a deviation of -1.41 percent to +2.23 percent. Normalized data for this run is contained in Figure 24. Although this run provided encouraging results, the three subsequent runs had very different profiles. The flow had a test core of only 20 inches and much larger deviations in Pitot pressure. Figure 25 contains data from one of these runs (2341) showing a Pitot pressure of 4.67 psia with deviations of -7.6 percent to +6.5 percent.

At this point, the assumption was made that the first run on throat set 2 (run 2338) was the nominal Mach 18 flow to expect. It was assumed that the poorer flow quality obtained in the subsequent runs was the result of some anomaly that needed to be accounted for and corrected. The calibration rake was installed for runs 2343 - 2346. The objective of these runs was to document the flow profile at various tunnel stations as noted in Table 3. The flow profile observed in run 2338 was not duplicated in any of these runs. Data for run 2343 is shown in Figure 26 of normalized Pitot pressures and in Table 5.

The remaining Mach 18 runs were made in an attempt to repeat the flow profile observed on run 2338 and to explain the flow character observed on subsequent runs. Factors that could produce the observed anomalies were identified and tests were run to determine their impact on flow quality. This series of diagnostic runs is described in Appendix A.

During the diagnostic series two types of flow profiles had been observed. Most of the runs have a 20-inch core with large deviations in the radial distribution of flow properties while a minority of runs have a 30-inch core with smaller deviations. Since no cause for this anomaly was determined during the diagnostic series two courses of action were pursued. The first was to utilize recently acquired CFD codes to examine the Mach 18 flow profile anomalies. The results from this effort will be discussed later. The second was to explore a lower Mach number. By lowering the Mach number we would not be using as much supercooling and not running the tunnel and nozzle so far off design.

RESULTS WITH MACH 16.5 THROAT HARDWARE

As discussed previously under NOZZLE THROAT HARDWARE, the throat piece of hardware set 3 was modified to produce Mach 16.5 flow. Run 2373 was the first run with this modified throat and the results were verified with the repeat run, 2374. The resulting flow had a core size of 24 inches and a Pitot pressure of 6.6 psia with deviations of -5.3 percent to +1.3 percent as shown in Figure 27 and Table 6.

Run 2377 was a calibration run for Mach 16.5 at station 2. Flow quality improved in this station. The core is 28 inches and the Pitot pressure is 6.38 psia with deviations of -1.1 percent to +1.3 percent. Data for this run is provided in Figure 28 and Table 7.

Station 3 was to be calibrated during run 2378. However, the flow had a 40-inch core and the run proved to be anomalous. Run 2379 was made immediately after run 2378 and the flow in station 3 correlated well with the calibrations at stations 1 and 2. The core size is 30 inches and the Pitot pressure is 5.96 psia with deviations of -0.9 percent to +4.1 percent. Data is contained in Figure 29 and Table 8.

To complete the calibration of the Mach 16.5 throat, data was taken on an aerodynamic shape. The blunt cone model was installed to obtain force and moment, pressure and heat transfer data. The data correlated well with nonsupercooled data taken at Mach 14 and predictions at Mach 18. No anomalies were discovered. Summaries of flow conditions for Mach 16.5 and Mach 18 are provided in Tables 9 and 10, respectively.

COMPUTATIONAL FLUID DYNAMICS (CFD) ANALYSIS

Computational Fluid Dynamics (CFD) codes were used together with experimental results to analyze the resulting flow. The codes were obtained through a Memorandum of Agreement with NASA-Langley Research Center. The codes, NASCRIN and EXP2DS, utilized a full Navier-Stokes (NS) solution over the Subsonic-Transonic region of the nozzle and a Parabolized Navier-Stokes (PNS) solution over the supersonic-hypersonic region of the nozzle. Test cases were performed at Mach 14 to verify the accuracy of the codes (see

References 11 and 12). Additional information on this analysis is contained in References 11 and 13.

The first issue explored was the nozzle wall boundary layer state. To determine if the two different types of profiles obtained exhibited two different boundary layer states, nozzle wall heat transfer rates were generated for laminar and turbulent boundary layers. Using nozzle wall thermocouple measurements in conjunction with CFD predictions, it was determined that the nozzle wall boundary layer is in a turbulent state for all runs.

The codes were run for both Mach 18 and Mach 16.5 flow at station 1. For both throat contours, the code predictions agreed with the experimental profile data except for runs 2338, 2343, 2370 and 2378 as described in Reference 13. These runs exhibited a larger uniform core with smaller Pitot pressure uniformity deviations where as the remaining runs exhibited smaller cores with larger Pitot pressure deviations.

The CFD calculations offered an explanation for the behavior on the majority of the runs. For the Mach 18 throat, the nozzle actually overexpands the flow along the nozzle centerline to a Mach number of 24. A system of weak oblique shock waves then compress the flow resulting in an exit Mach number of 17.5. The 20-inch core size results from the intersection of these oblique shock waves with the test cell 10 inches from the centerline. The Mach 16.5 throat also overexpands the flow along the nozzle centerline but the maximum Mach number is only 20. For this case oblique shocks are present but they are much weaker. The Mach 16.5 core size is larger (24 inches) and the deviations are reduced from the Mach 18 configuration.

A possible explanation for the runs that produced a free-stream flow with a larger core and a flatter profile (runs 2338, 2343, 2370 and 2378) assumes condensation in the flow upstream of the test cell. Although the optical detecting system showed the test cell region to be condensation free, no measurements were taken in the nozzle. The presence of condensation in the nozzle would lower the centerline Mach number resulting in little or no overexpansion. In the absence of overexpansion, no oblique shock waves are formed resulting in a larger core size and less variation in flow properties. Condensation upstream of the test cell might be induced by the presence of water vapor or other particles.

A possible source of water vapor might occur when the heater is exposed to atmosphere for an extended period. Prior to making a tunnel run, the heater vessel is evacuated to approximately 1 mmHg. The heater typically remains isolated from atmosphere until it is opened for maintenance or to change the heater package for a different Mach number. Runs 2338 and 2370 followed runs with different Mach numbers. In both cases the heater had to be opened to install the Mach 14 heater package. Prior to run 2343 there was a 3-month break in tunnel operation and the heater had been opened during this period for routine maintenance. Before run 2378 the heater had been opened to install thermocouples and replace the heater element as part of an in-house study of heater vessel temperatures. Thus, there is a possibility that when the heater package is exposed to atmosphere, air or water vapor molecules attach to the graphite liner or heater element. During the first run following exposure, these contaminants, if present, are outgassed into the pure nitrogen working gas. The flow contaminants would stimulate the condensation process thus altering the flow expansion process and the resulting flow profile. This theory has not yet been proved but will be studied more in the future. For the time being, the Mach 16.5 condition is less stringent and provides acceptable flow quality.

FUTURE PLANS

Future efforts for improving flow quality will investigate optimizing the nozzle throat insert design. New throat contours will be designed to eliminate overexpansion of the flow in the nozzle. CFD codes will be used to evaluate the flow produced by these new contours.

Additional measurements are planned to study various flow characteristics. In the test cell, independent measurements of flow properties will be made to determine any deviation from equilibrium. A laser directed upstream along the nozzle centerline will be used along with light scattering optics to detect the presence of condensation in the tunnel nozzle.

SUMMARY

The study described in this report shows that it is possible to use supercooling together with a modified nozzle throat section to increase the Mach number capability of a hypersonic facility without major alterations. The phenomenon of supercooling has been used to reduce the required supply temperature from 4300°R to 3225°R. This allows the existing Tunnel 9 Mach 14 heater to be used without modification. Also, a modified throat section was installed in the existing Mach 14 nozzle to produce the proper throat-to-exit area ratio required for Mach 16.5 and Mach 18 flow.

Forty-one runs have been made to support this program. For the Mach 16.5 throat, approximately 15°R of supercooling was utilized. The resulting flow has a 28-inch core with deviations in Pitot pressure of -1.1 percent to +1.3 percent. The run time is approximately 3.5 seconds. Laser light scattering was used to monitor the presence of condensation. The flow was observed to be in a supercooled state and the free-stream flow was condensation free in the test cell.

This method of replacing throat inserts has proven to be very successful in upgrading the capability of Tunnel 9. Future studies will use advanced CFD methods to optimize nozzle throat contours in an attempt to eliminate overexpansion of the flow in the nozzle and to improve flow quality.

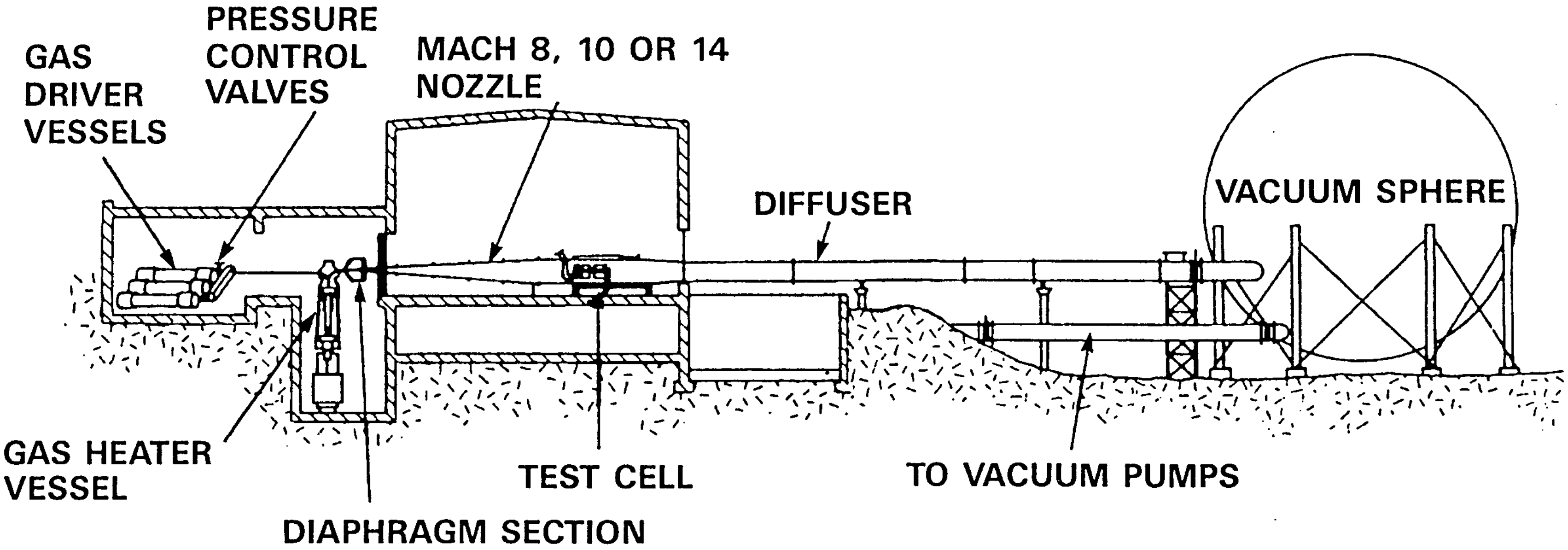


FIGURE 1. SCHEMATIC OF HYPERVELOCITY WIND TUNNEL NO. 9

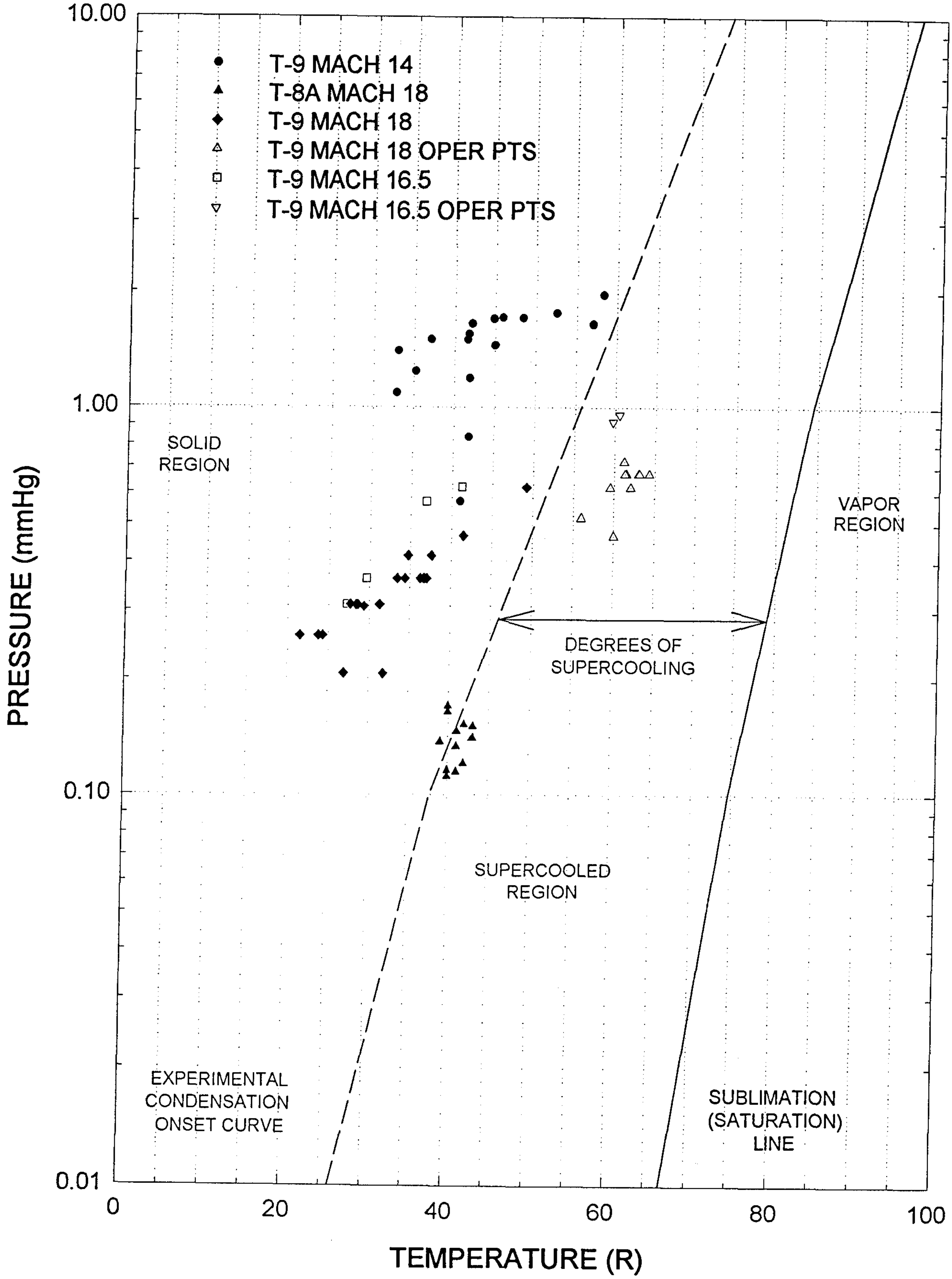


FIGURE 2. DATA FOR THE DISAPPEARANCE AND ONSET OF CONDENSATION

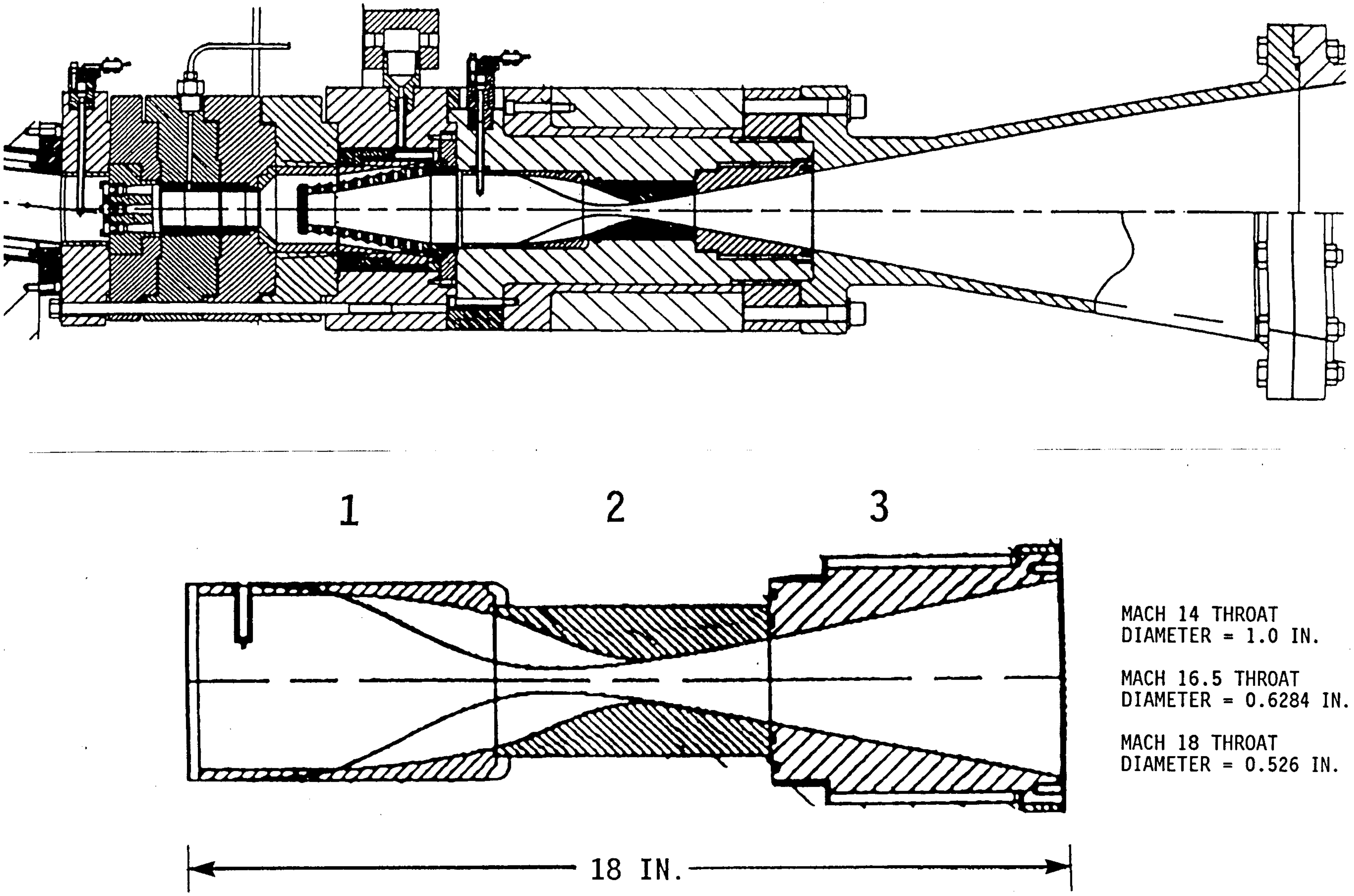
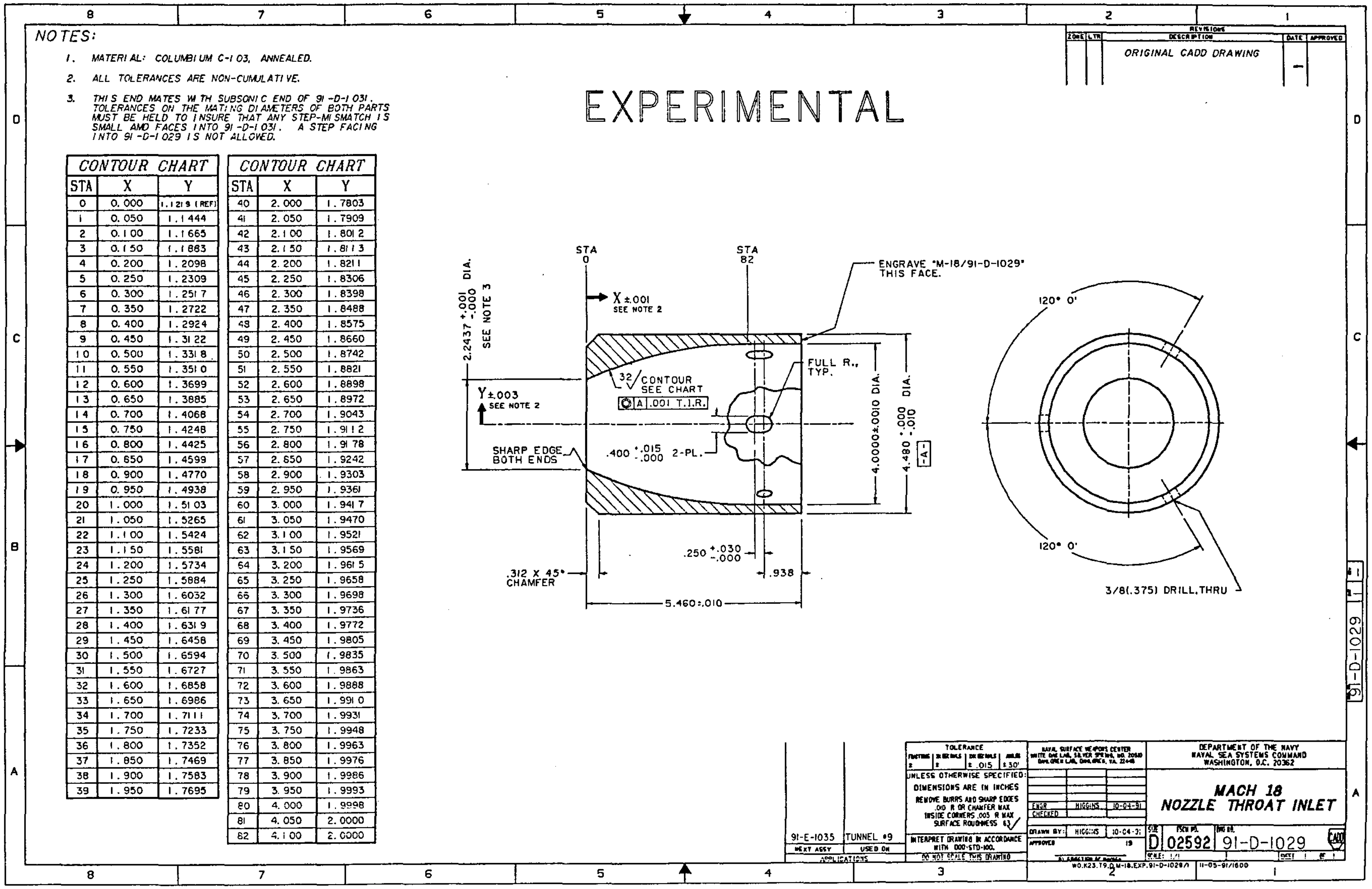


FIGURE 3. MACH 14 NOZZLE THROAT SECTION WITH MACH 18 INSERT



NOTES:

1. MATERIAL: COLUMBIUM C-103, ANNEALED.
2. ALL TOLERANCES ARE NON-CUMULATIVE.
3. THIS END MATES WITH SUBSONIC END OF 91-D-1031. TOLERANCES ON THE MATING DIAMETERS OF BOTH PARTS MUST BE HELD TO INSURE THAT ANY STEP-MISMATCH IS SMALL AND FACES INTO 91-D-1031. A STEP FACING INTO 91-D-1029 IS NOT ALLOWED.

CONTOUR CHART

STA	X	Y
0	0.000	1.1219 (REF)
1	0.050	1.1444
2	0.100	1.1665
3	0.150	1.1883
4	0.200	1.2098
5	0.250	1.2309
6	0.300	1.2517
7	0.350	1.2722
8	0.400	1.2924
9	0.450	1.3122
10	0.500	1.3318
11	0.550	1.3510
12	0.600	1.3699
13	0.650	1.3885
14	0.700	1.4068
15	0.750	1.4248
16	0.800	1.4425
17	0.850	1.4599
18	0.900	1.4770
19	0.950	1.4938
20	1.000	1.5103
21	1.050	1.5265
22	1.100	1.5424
23	1.150	1.5581
24	1.200	1.5734
25	1.250	1.5884
26	1.300	1.6032
27	1.350	1.6177
28	1.400	1.6319
29	1.450	1.6458
30	1.500	1.6594
31	1.550	1.6727
32	1.600	1.6858
33	1.650	1.6986
34	1.700	1.7111
35	1.750	1.7233
36	1.800	1.7352
37	1.850	1.7469
38	1.900	1.7583
39	1.950	1.7695

CONTOUR CHART

STA	X	Y
40	2.000	1.7803
41	2.050	1.7909
42	2.100	1.8012
43	2.150	1.8113
44	2.200	1.8211
45	2.250	1.8306
46	2.300	1.8398
47	2.350	1.8488
48	2.400	1.8575
49	2.450	1.8660
50	2.500	1.8742
51	2.550	1.8821
52	2.600	1.8898
53	2.650	1.8972
54	2.700	1.9043
55	2.750	1.9112
56	2.800	1.9178
57	2.850	1.9242
58	2.900	1.9303
59	2.950	1.9361
60	3.000	1.9417
61	3.050	1.9470
62	3.100	1.9521
63	3.150	1.9569
64	3.200	1.9615
65	3.250	1.9658
66	3.300	1.9698
67	3.350	1.9736
68	3.400	1.9772
69	3.450	1.9805
70	3.500	1.9835
71	3.550	1.9863
72	3.600	1.9888
73	3.650	1.9910
74	3.700	1.9931
75	3.750	1.9948
76	3.800	1.9963
77	3.850	1.9976
78	3.900	1.9986
79	3.950	1.9993
80	4.000	1.9998
81	4.050	2.0000
82	4.100	2.0000

FIGURE 4. MACH 18 NOZZLE THROAT INLET SECTION

REVISIONS

ZONE	LTR	DESCRIPTION	DATE	APPROVED
		ORIGINAL CADD DRAWING		

NOTES:

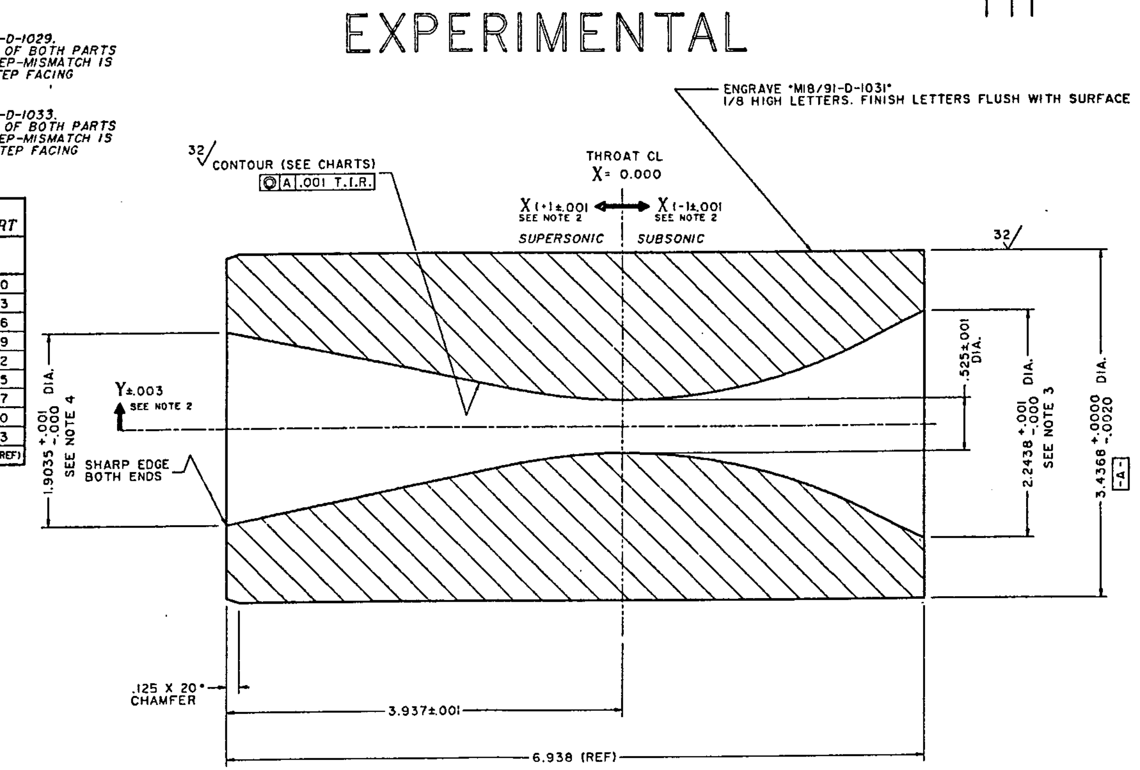
1. MATERIAL: COLUMBIUM C-103, ANNEALED.
2. ALL TOLERANCES ARE NON-CUMULATIVE.
3. THIS END MATES WITH SMALL END OF 91-D-1029. TOLERANCES ON THE MATING DIAMETERS OF BOTH PARTS MUST BE HELD TO INSURE THAT ANY STEP-MISMATCH IS SMALL AND FACES INTO 91-D-1031. A STEP FACING INTO 91-D-1029 IS NOT ALLOWED.
4. THIS END MATES WITH SMALL END OF 91-D-1033. TOLERANCES ON THE MATING DIAMETERS OF BOTH PARTS MUST BE HELD TO INSURE THAT ANY STEP-MISMATCH IS SMALL AND FACES INTO 91-D-1033. A STEP FACING INTO 91-D-1031 IS NOT ALLOWED.

SUPERSONIC CONTOUR CHART

X(+)	Y
0.000	0.2625 (REF)
0.100	0.2635
0.200	0.2665
0.300	0.2716
0.400	0.2788
0.500	0.2880
0.600	0.2992
0.700	0.3122
0.800	0.3268
0.900	0.3429
1.000	0.3602
1.100	0.3785
1.200	0.3976
1.300	0.4172
1.400	0.4372
1.500	0.4574
1.600	0.4777
1.700	0.4979
1.800	0.5182
1.900	0.5385
2.000	0.5588
2.100	0.5791
2.200	0.5994
2.300	0.6197
2.400	0.6400
2.500	0.6603
2.600	0.6806
2.700	0.7008
2.800	0.7211
2.900	0.7414
3.000	0.7617

SUPERSONIC CONTOUR CHART

X(+)	Y
3.100	0.7820
3.200	0.8023
3.300	0.8226
3.400	0.8429
3.500	0.8632
3.600	0.8835
3.700	0.9037
3.800	0.9240
3.900	0.9443
3.937	0.9518 (REF)



SUBSONIC CONTOUR CHART

X(-)	Y
0.000	0.2625 (REF)
0.100	0.2634
0.200	0.2662
0.300	0.2708
0.400	0.2773
0.500	0.2857
0.600	0.2960
0.700	0.3082
0.800	0.3222
0.900	0.3382
1.000	0.3561
1.100	0.3760
1.200	0.3979
1.300	0.4218
1.400	0.4477
1.500	0.4757
1.600	0.5057
1.700	0.5379
1.800	0.5723
1.900	0.6089
2.000	0.6478
2.100	0.6890
2.200	0.7326
2.300	0.7786
2.400	0.8272
2.500	0.8783
2.600	0.9298
2.700	0.9798
2.800	1.0285
2.900	1.0757
3.001	1.1219 (REF)

NEXT ASSY	USED ON
91-E-1035	TUNNEL #9

APPLICATIONS

TOLERANCE ±.005 ±30'
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
REMOVE BURRS AND SHARP EDGES .010 R OR CHAMFER MAX
INSIDE CORNERS .005 R MAX
SURFACE ROUGHNESS 63/
INTERPRET DRAWING IN ACCORDANCE WITH DOD-STD-100.
DO NOT SCALE THIS DRAWING

NAVAL SURFACE WEAPONS CENTER
WHITE OAK LAB, SILVER SPRING, MD. 20910
DAHLGREN LAB, DAHLGREN, VA. 22448

ENGR HIGGINS 10-04-91
CHECKED
DRAWN BY: HIGGINS 10-04-91
APPROVED 19

DEPARTMENT OF THE NAVY
NAVAL SEA SYSTEMS COMMAND
WASHINGTON, D.C. 20362

MACH 18
NOZZLE THROAT

SIZE D FSCM NO. 02592 DWG NO. 91-D-1031
SCALE: 2/1 SHEET 1 OF 1

WO.K23.T9.DM-18.EXP.91-D-1031/1 11-05-91/1630

FIGURE 5. MACH 18 NOZZLE THROAT SECTION

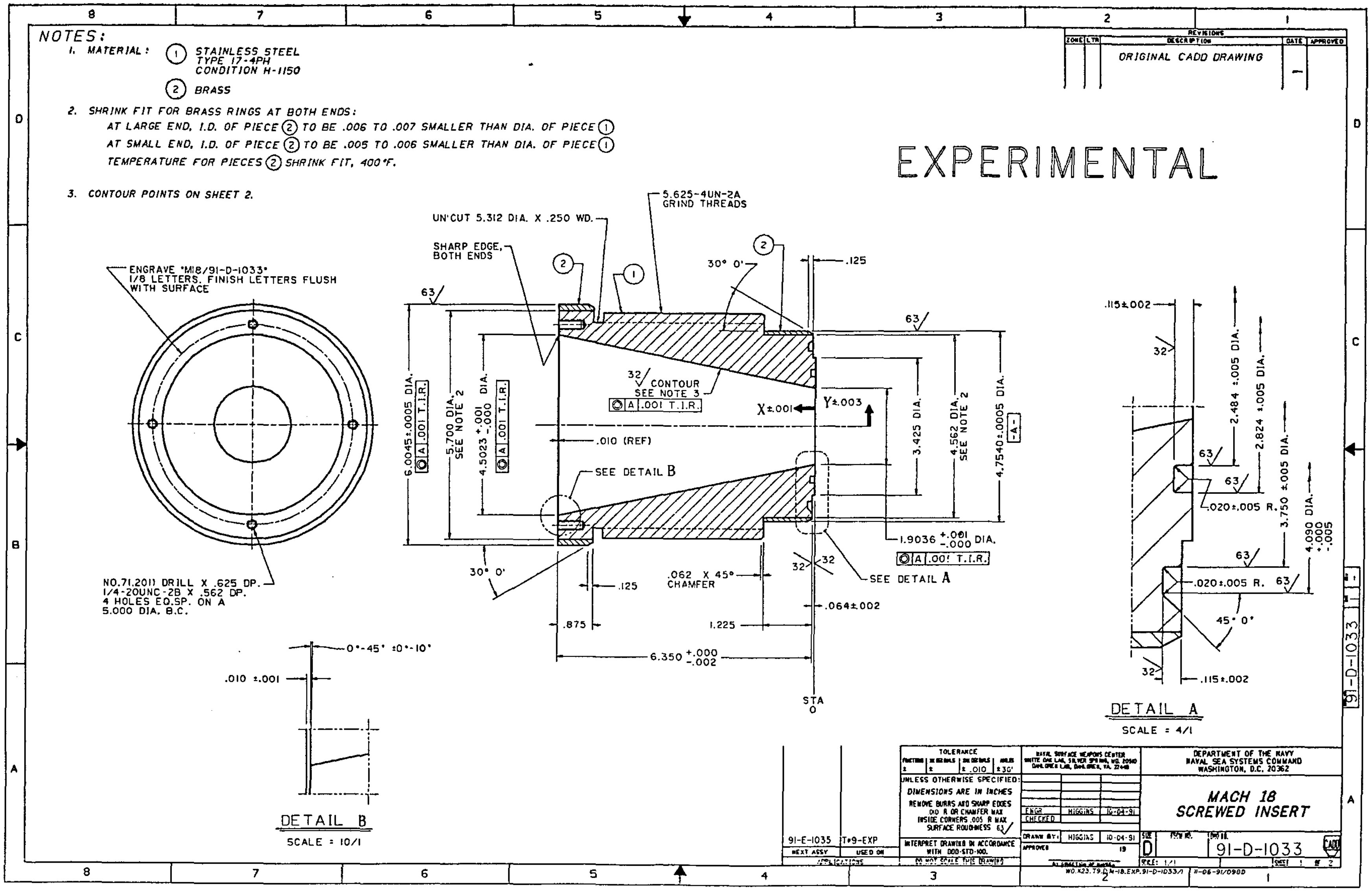
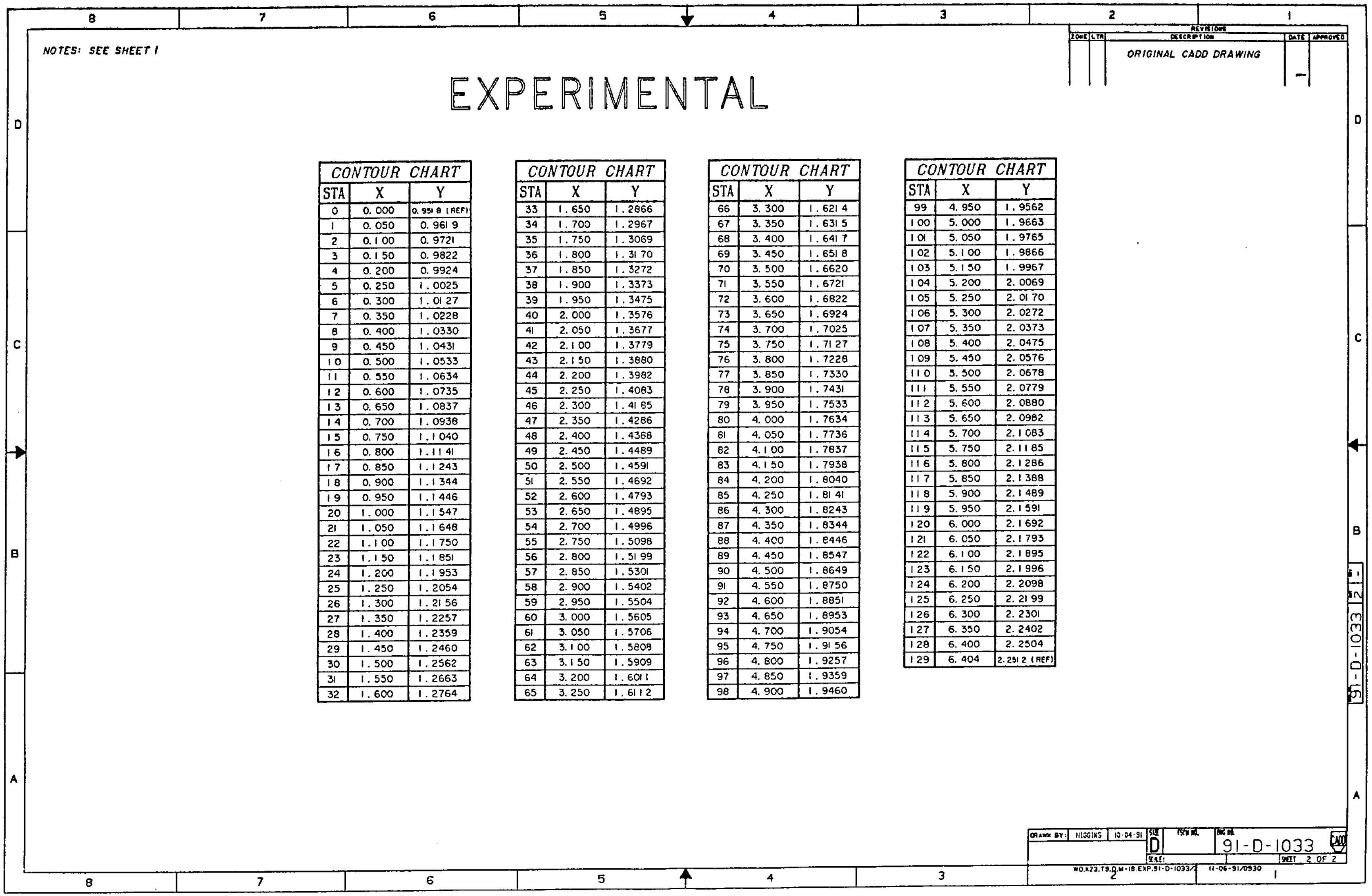


FIGURE 6. MACH 18 NOZZLE SCREWED INSERT SECTION



NOTES: SEE SHEET 1

EXPERIMENTAL

CONTOUR CHART

STA	X	Y
0	0.000	0.9518 (REF)
1	0.050	0.9619
2	0.100	0.9721
3	0.150	0.9822
4	0.200	0.9924
5	0.250	1.0025
6	0.300	1.0127
7	0.350	1.0228
8	0.400	1.0330
9	0.450	1.0431
10	0.500	1.0533
11	0.550	1.0634
12	0.600	1.0735
13	0.650	1.0837
14	0.700	1.0938
15	0.750	1.1040
16	0.800	1.1141
17	0.850	1.1243
18	0.900	1.1344
19	0.950	1.1446
20	1.000	1.1547
21	1.050	1.1648
22	1.100	1.1750
23	1.150	1.1851
24	1.200	1.1953
25	1.250	1.2054
26	1.300	1.2156
27	1.350	1.2257
28	1.400	1.2359
29	1.450	1.2460
30	1.500	1.2562
31	1.550	1.2663
32	1.600	1.2764
33	1.650	1.2866
34	1.700	1.2967
35	1.750	1.3069
36	1.800	1.3170
37	1.850	1.3272
38	1.900	1.3373
39	1.950	1.3475
40	2.000	1.3576
41	2.050	1.3677
42	2.100	1.3779
43	2.150	1.3880
44	2.200	1.3982
45	2.250	1.4083
46	2.300	1.4185
47	2.350	1.4286
48	2.400	1.4388
49	2.450	1.4489
50	2.500	1.4591
51	2.550	1.4692
52	2.600	1.4793
53	2.650	1.4895
54	2.700	1.4996
55	2.750	1.5098
56	2.800	1.5199
57	2.850	1.5301
58	2.900	1.5402
59	2.950	1.5504
60	3.000	1.5605
61	3.050	1.5706
62	3.100	1.5808
63	3.150	1.5909
64	3.200	1.6011
65	3.250	1.6112
66	3.300	1.6214
67	3.350	1.6315
68	3.400	1.6417
69	3.450	1.6518
70	3.500	1.6620
71	3.550	1.6721
72	3.600	1.6822
73	3.650	1.6924
74	3.700	1.7025
75	3.750	1.7127
76	3.800	1.7228
77	3.850	1.7330
78	3.900	1.7431
79	3.950	1.7533
80	4.000	1.7634
81	4.050	1.7736
82	4.100	1.7837
83	4.150	1.7938
84	4.200	1.8040
85	4.250	1.8141
86	4.300	1.8243
87	4.350	1.8344
88	4.400	1.8446
89	4.450	1.8547
90	4.500	1.8649
91	4.550	1.8750
92	4.600	1.8851
93	4.650	1.8953
94	4.700	1.9054
95	4.750	1.9156
96	4.800	1.9257
97	4.850	1.9359
98	4.900	1.9460
99	4.950	1.9562
100	5.000	1.9663
101	5.050	1.9765
102	5.100	1.9866
103	5.150	1.9967
104	5.200	2.0069
105	5.250	2.0170
106	5.300	2.0272
107	5.350	2.0373
108	5.400	2.0475
109	5.450	2.0576
110	5.500	2.0678
111	5.550	2.0779
112	5.600	2.0880
113	5.650	2.0982
114	5.700	2.1083
115	5.750	2.1185
116	5.800	2.1286
117	5.850	2.1388
118	5.900	2.1489
119	5.950	2.1591
120	6.000	2.1692
121	6.050	2.1793
122	6.100	2.1895
123	6.150	2.1996
124	6.200	2.2098
125	6.250	2.2199
126	6.300	2.2301
127	6.350	2.2402
128	6.400	2.2504
129	6.404	2.2512 (REF)

FIGURE 6. (CONTINUED)

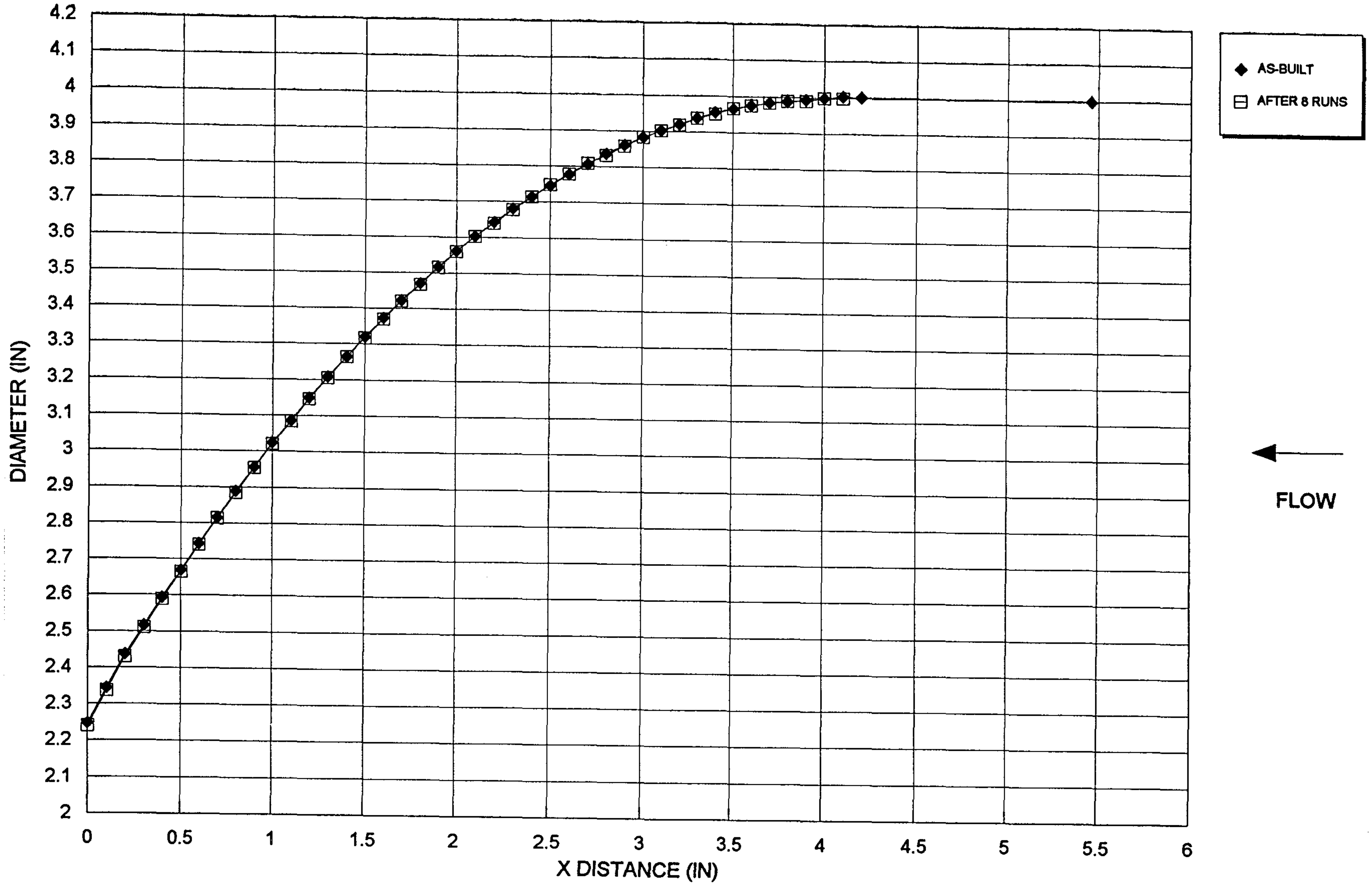


FIGURE 7. MACH 18 NOZZLE THROAT INLET SECTION: AS BUILT AND AFTER 8 RUNS

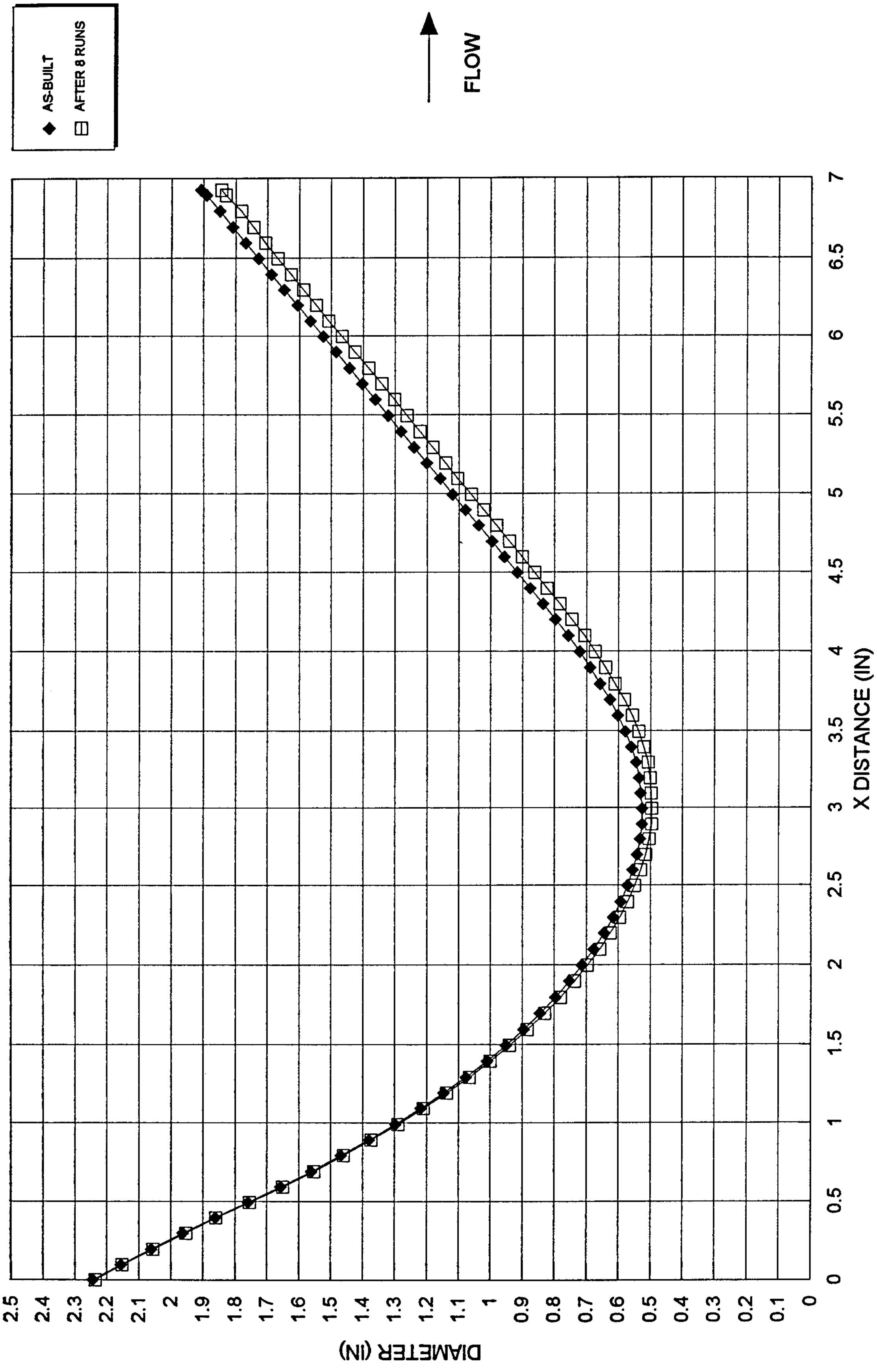


FIGURE 8. MACH 18 NOZZLE THROAT SECTION: AS BUILT AND AFTER 8 RUNS

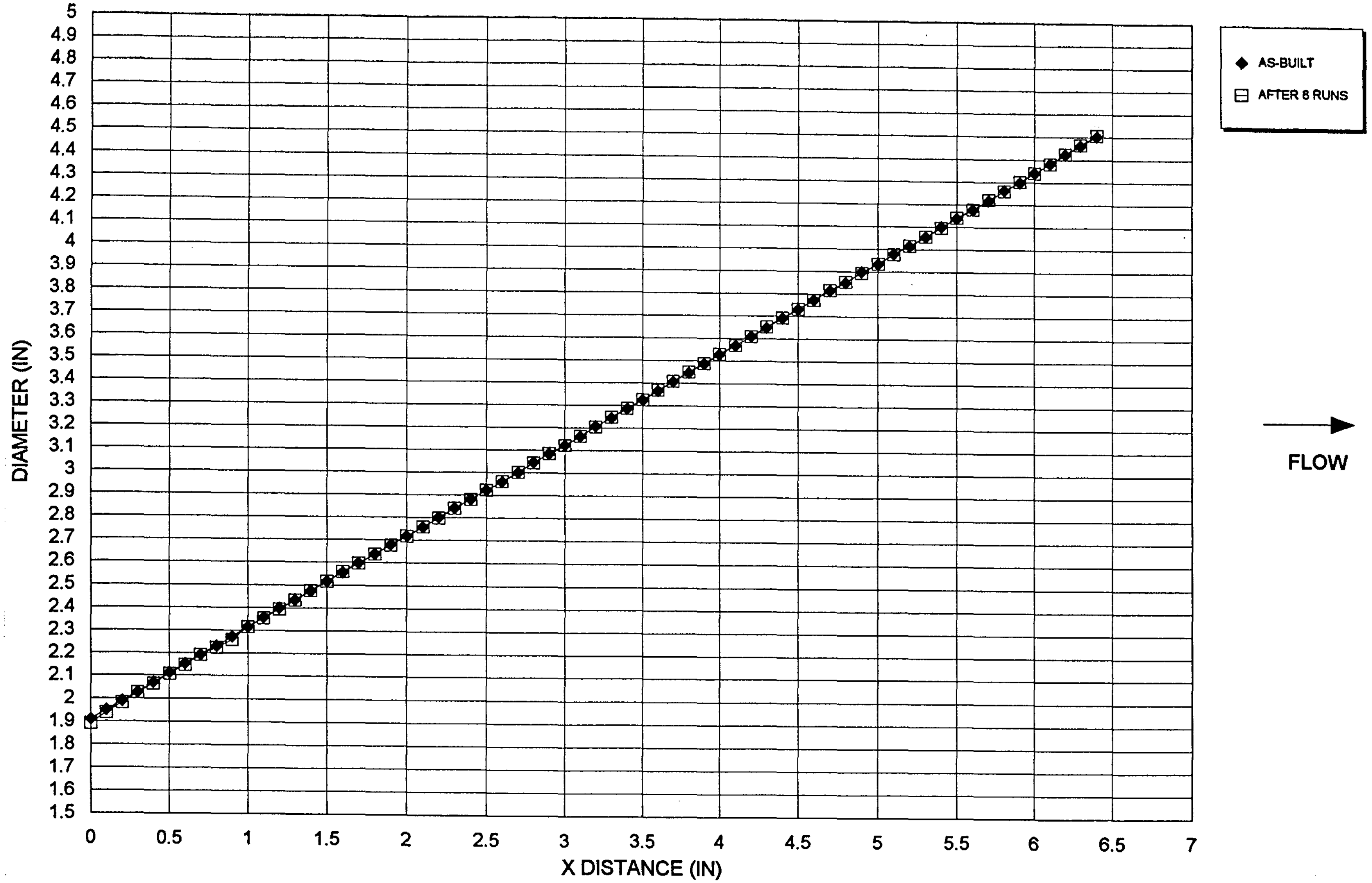


FIGURE 9. MACH 18 NOZZLE SCREWED INSERT SECTION: AS BUILT AND AFTER 8 RUNS

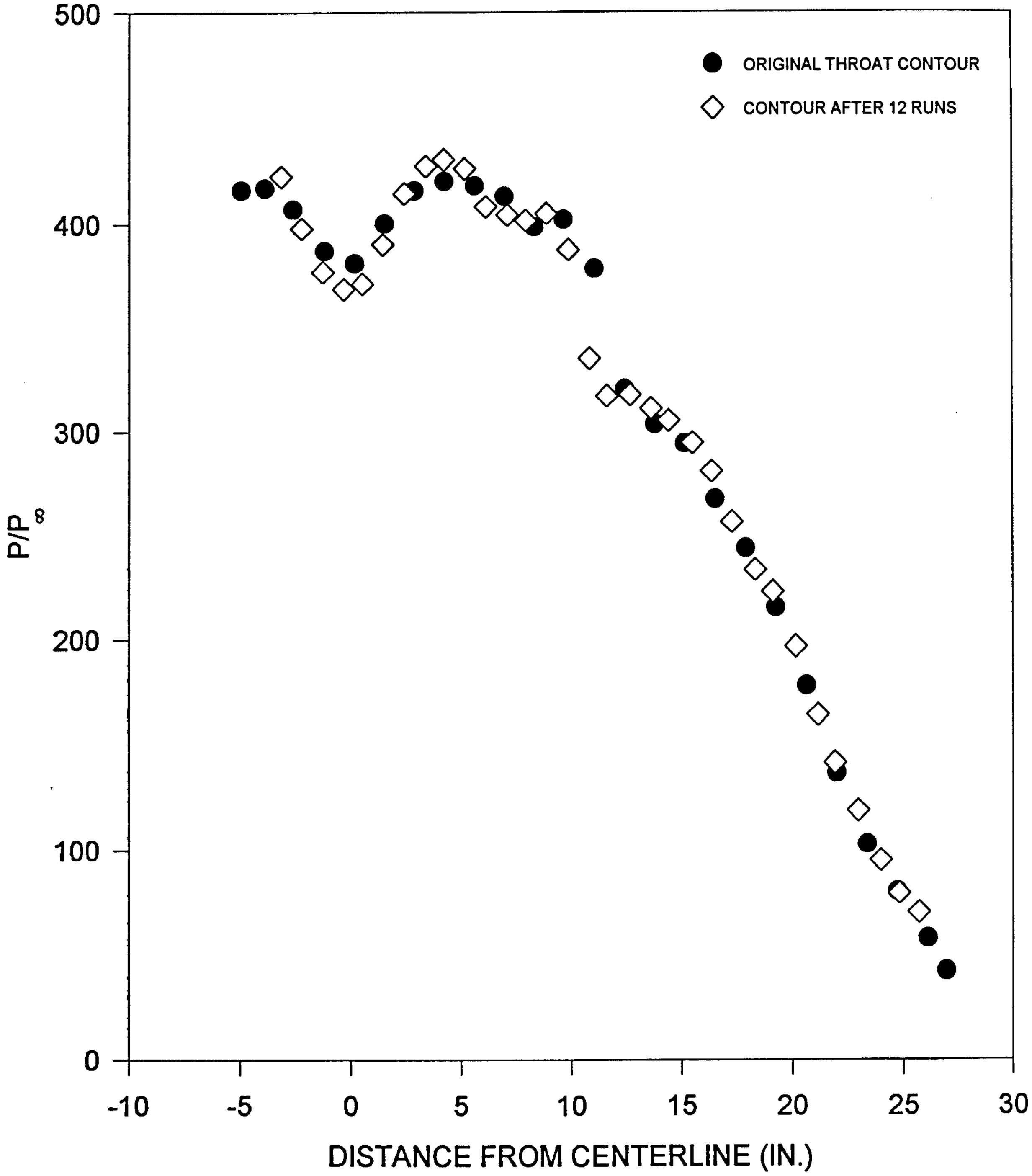


FIGURE 10. EFFECT OF THROAT CONTOUR CHANGE ON FLOW PROFILE

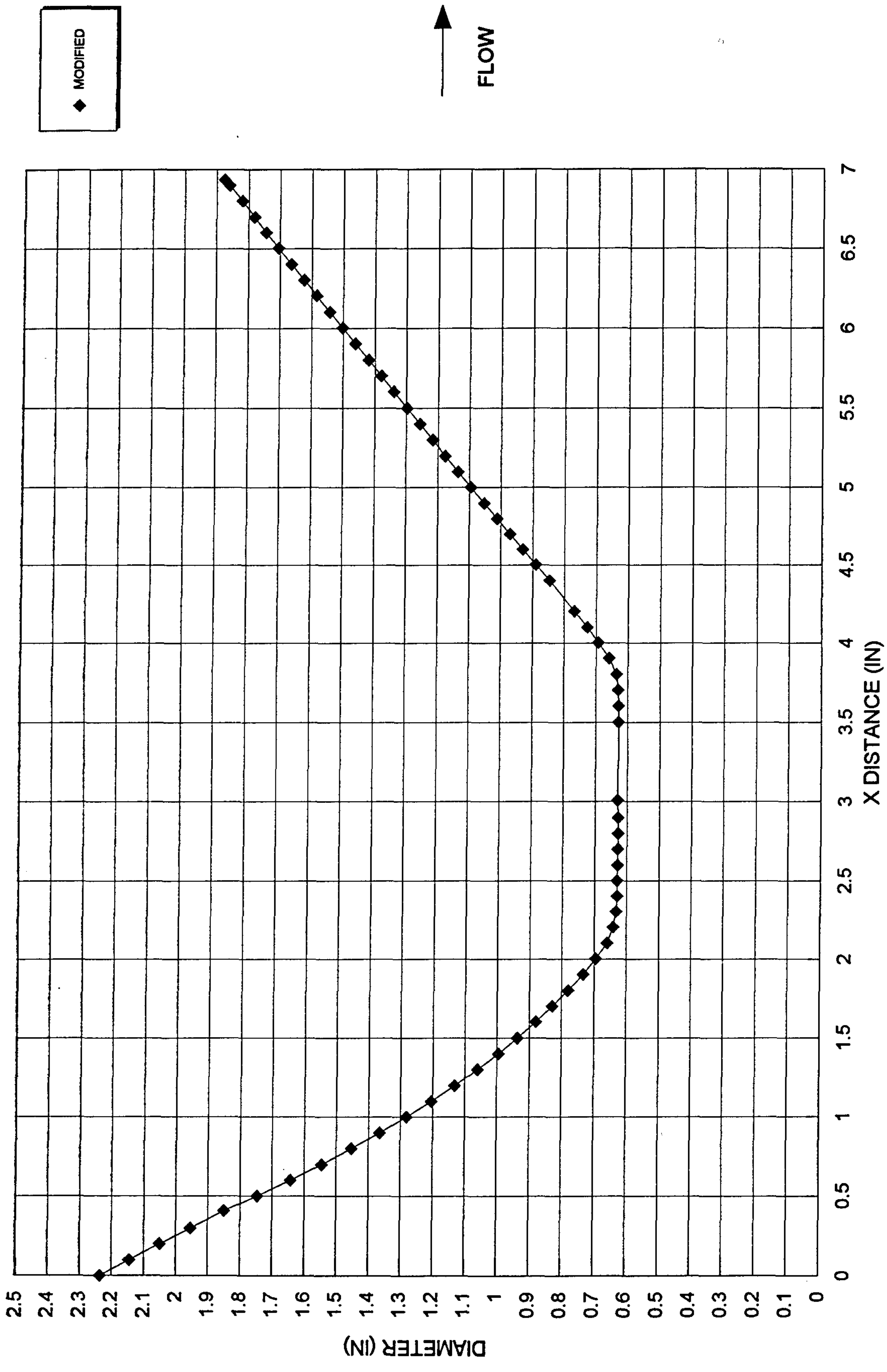


FIGURE 11. MACH 16.5 NOZZLE THROAT SECTION CONTOUR

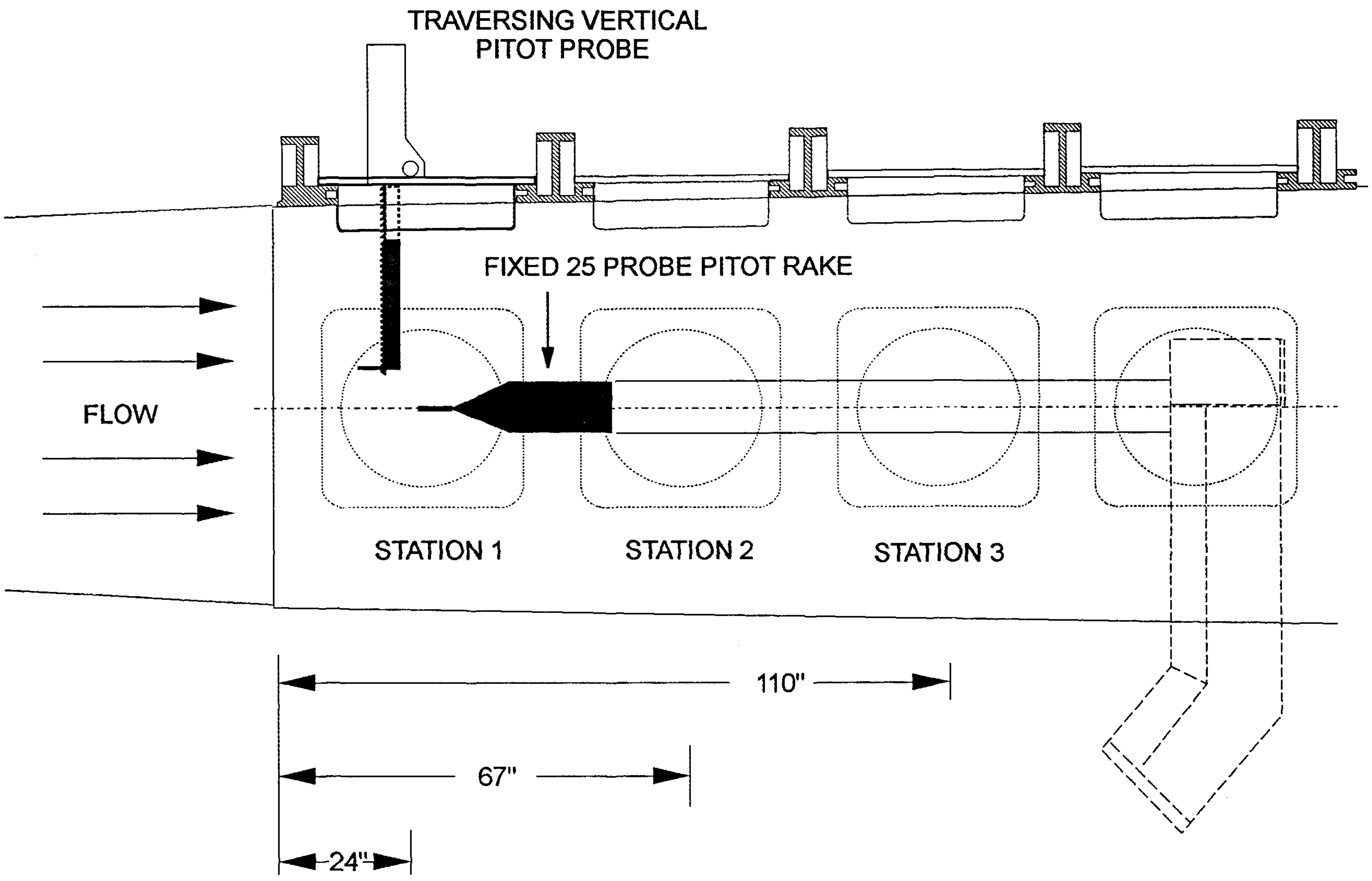


FIGURE 12. SCHEMATIC OF TEST SET-UP WITH FIXED AND TRANSVERSING PITOT RAKES

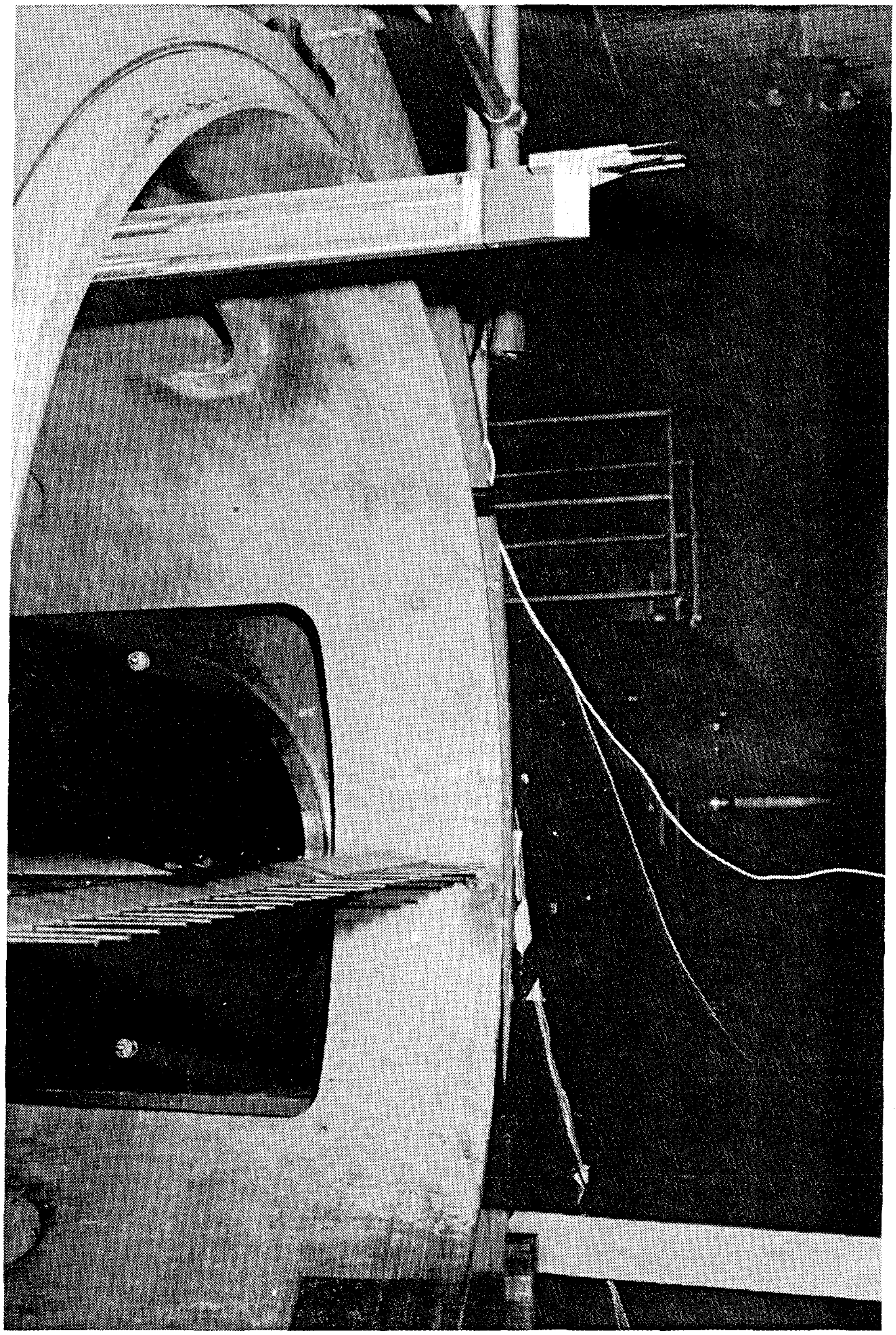


FIGURE 13. PHOTOGRAPH OF CALIBRATION AND TRAVERSING PITOT RAKES INSTALLED IN TUNNEL 9

TEMPERATURE INSTRUMENTATION

GAUGE	AXIAL DISTANCE * (INCHES)	RAY
T15	18.30	3
T35	18.30	3
T17	24.62	1
T37	24.62	3
T18	29.76	1
T28	29.76	2
T38	29.76	3
T48	29.76	4
T110	34.98	1
T310	34.98	3
T112	40.00	1
T312	40.00	3
T114	45.50	1
T314	5.50	3
T116	50.28	1
T216	50.28	2
T316	50.28	3
T416	50.28	4
T118	6.43	1
T318	56.43	3

PRESSURE INSTRUMENTATION

GAUGE	AXIAL DISTANCE * (INCHES)	RAY
P10	0.50	1
P30	0.50	3
P16	20.18	1
P26	20.18	2
P36	20.18	3
P46	20.18	4
P19	30.61	1
P39	30.61	3
P111	35.90	1
P311	35.90	3
P113	43.00	1
P213	43.00	2
P313	43.00	3
P413	43.00	4
P115	47.89	1
P315	47.89	3
P117	53.35	1
P217	53.35	2
P317	53.35	3
P417	53.35	4
PB1	59.50	1
PB2	59.50	2
PB3	59.50	3
PB4	59.50	4

* AXIAL DISTANCES MEASURED FROM VIRTUAL SHARP NOSE 11.572 INCHES UPSTREAM OF BLUNT NOSE

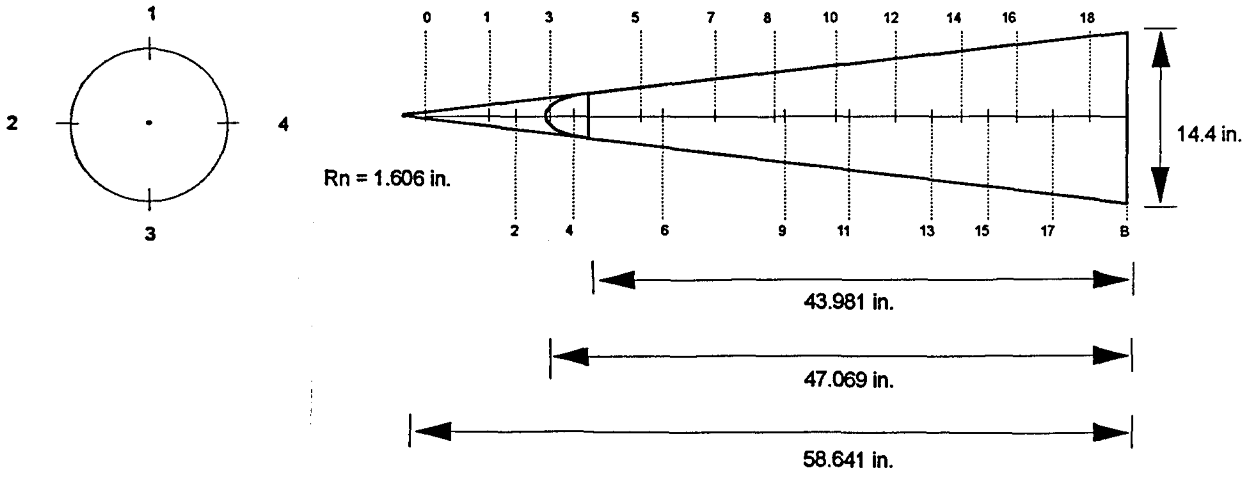


FIGURE 14. BLUNT CONE INSTRUMENTATION

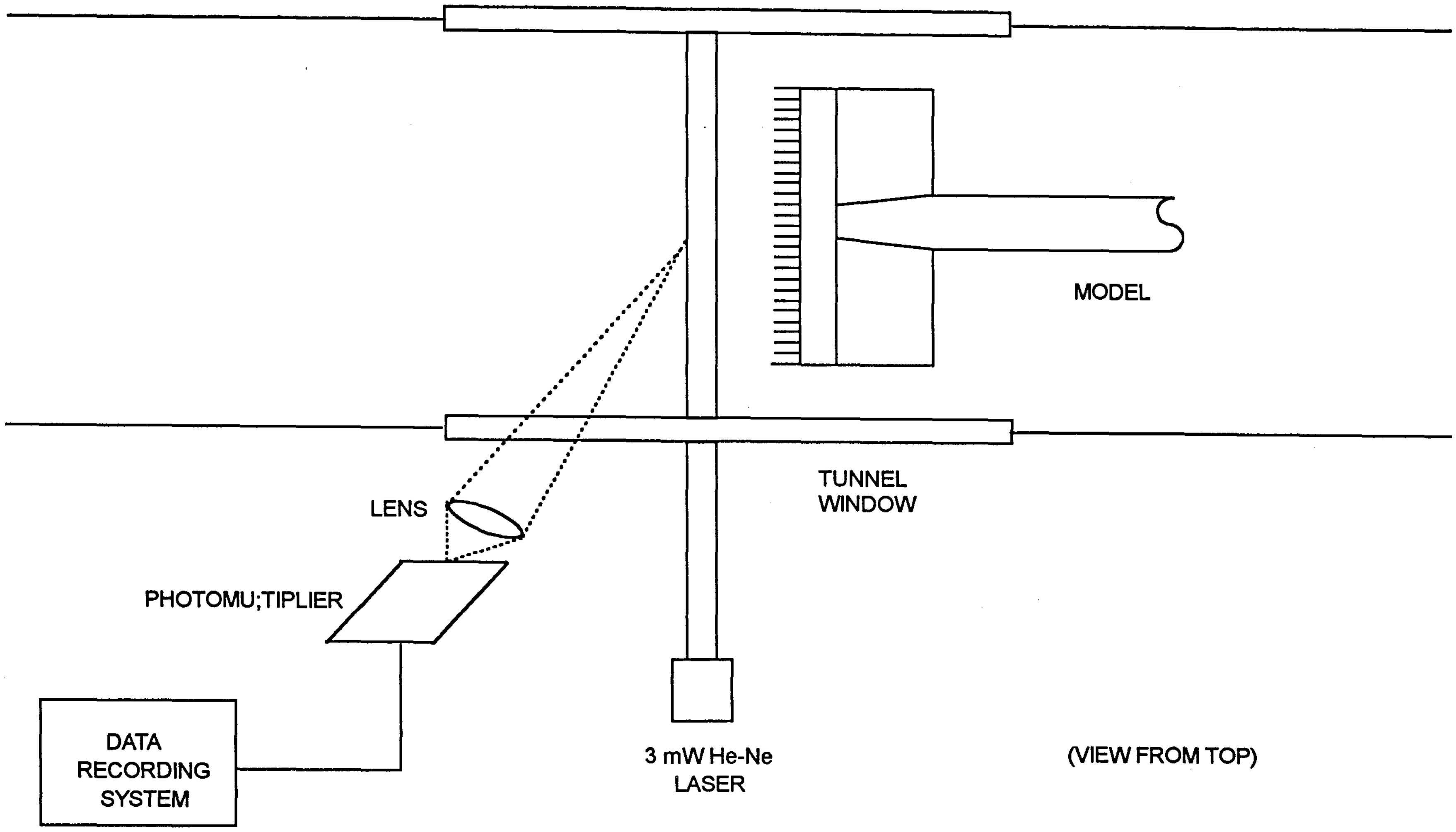


FIGURE 15. LASER LIGHT SCATTERING OPTICS

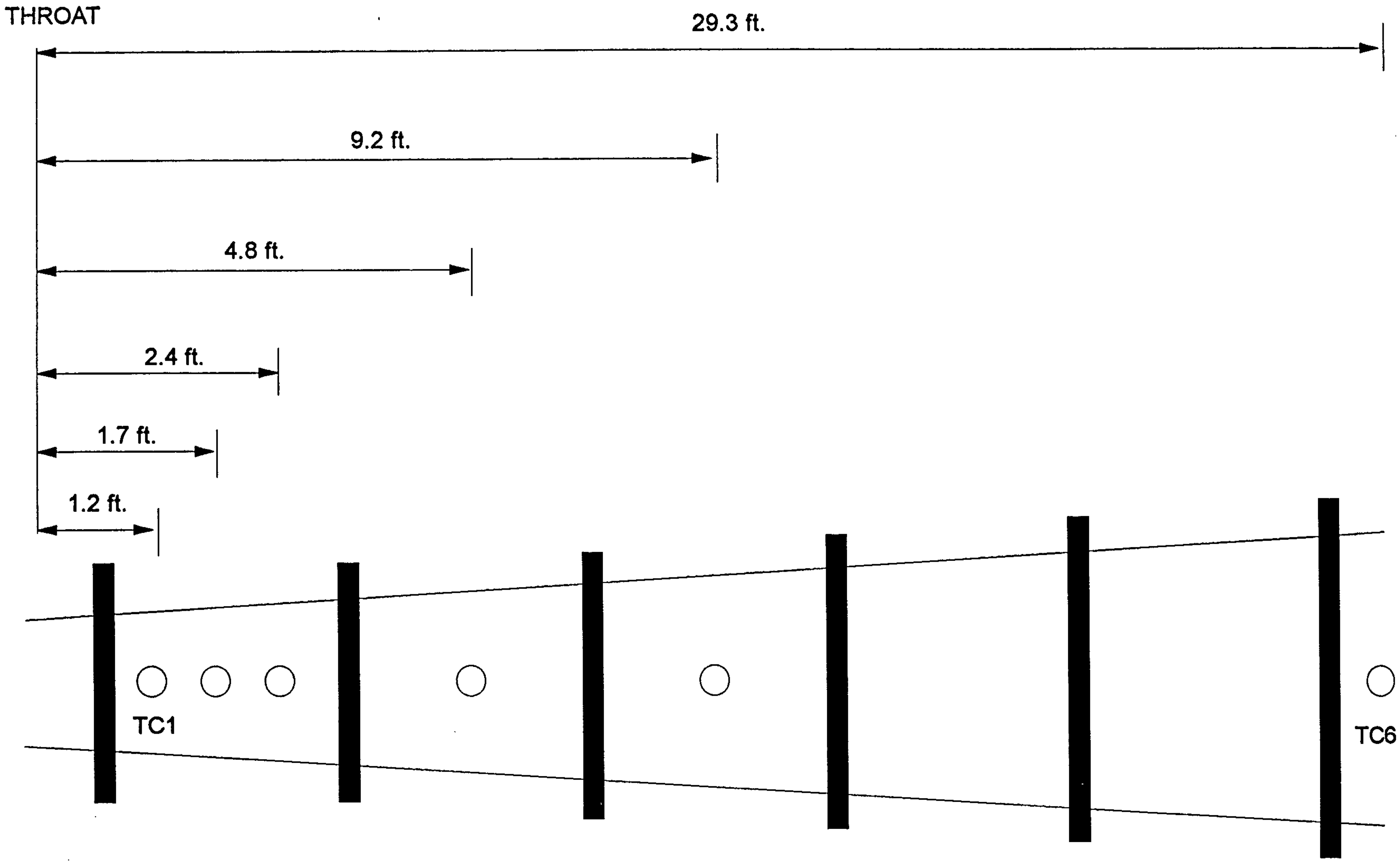


FIGURE 16. LOCATION OF NOZZLE WALL THERMOCOUPLES

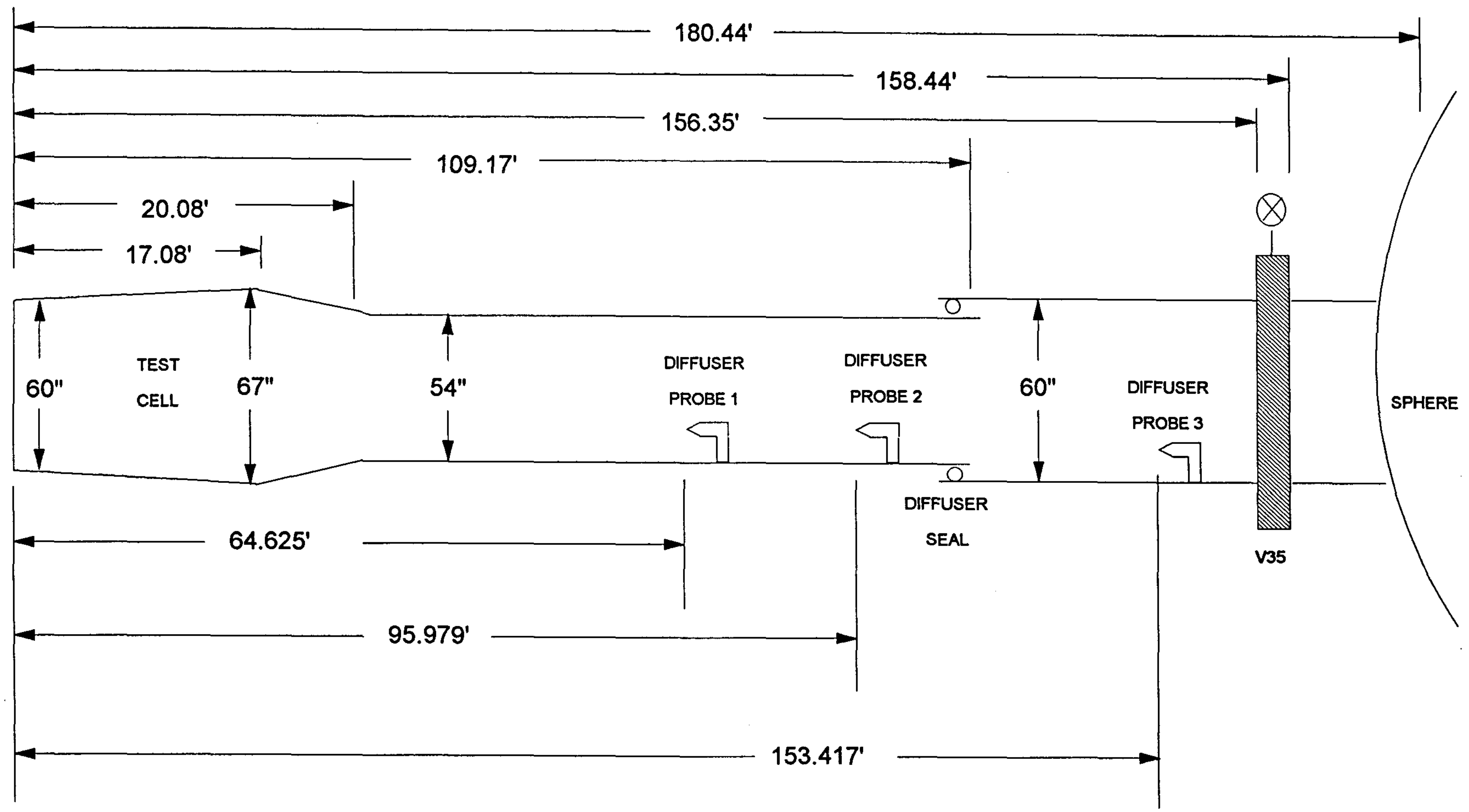


FIGURE 17. LOCATION OF DIFFUSER CONE STATIC PROBES

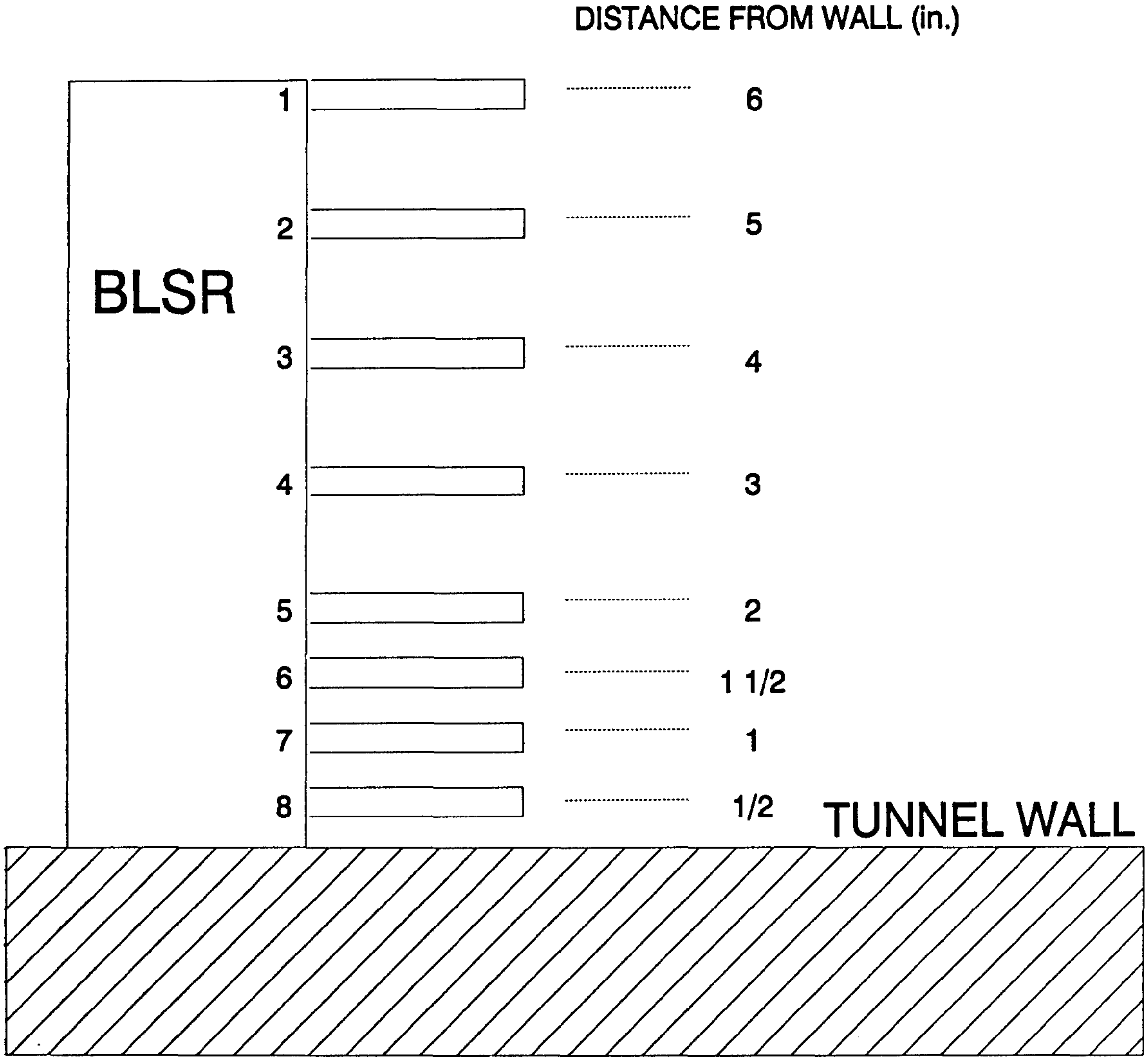


FIGURE 18. SHORT BOUNDARY-LAYER PITOT RAKE

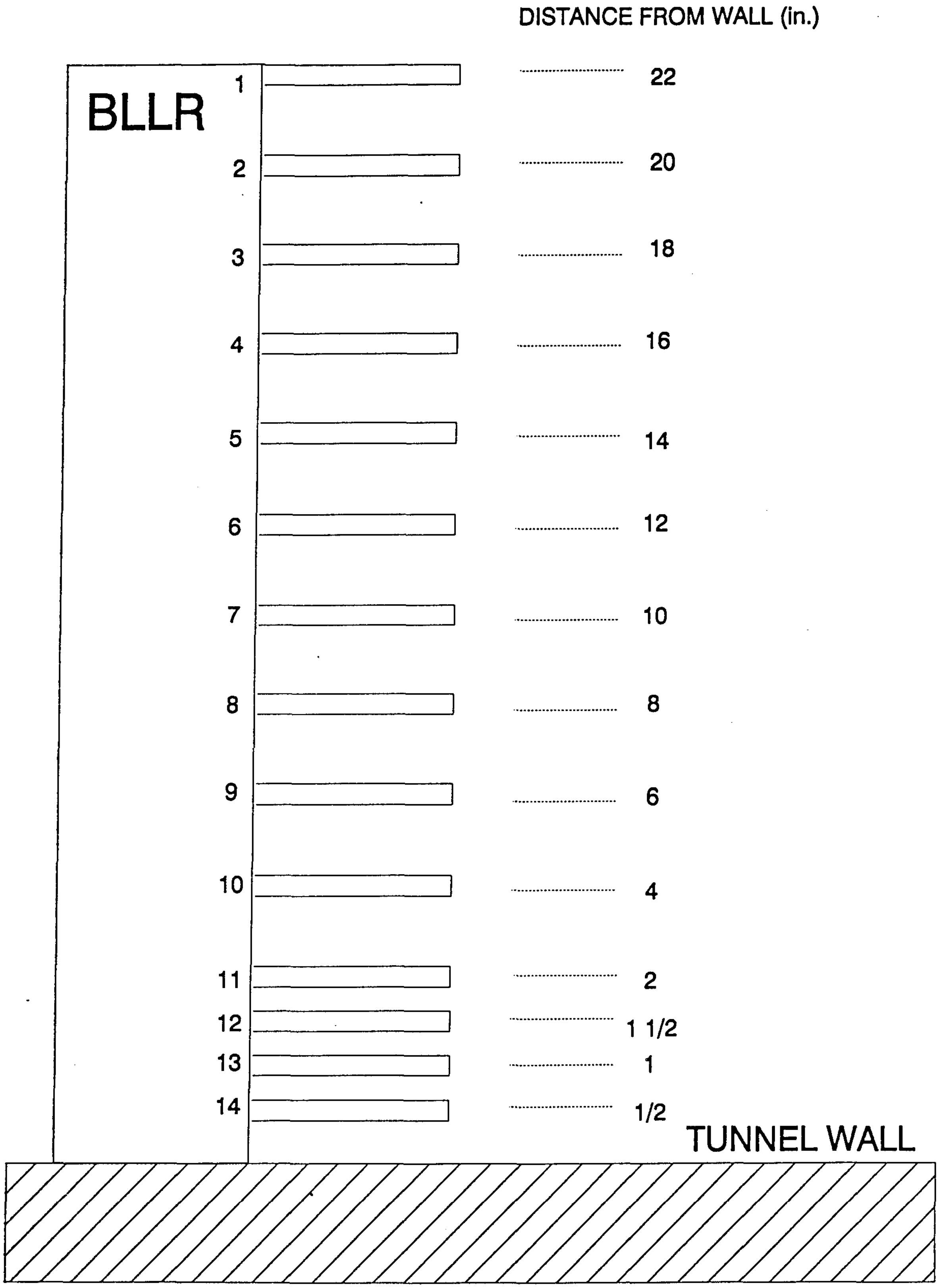


FIGURE 19. LONG BOUNDARY-LAYER PITOT RAKE

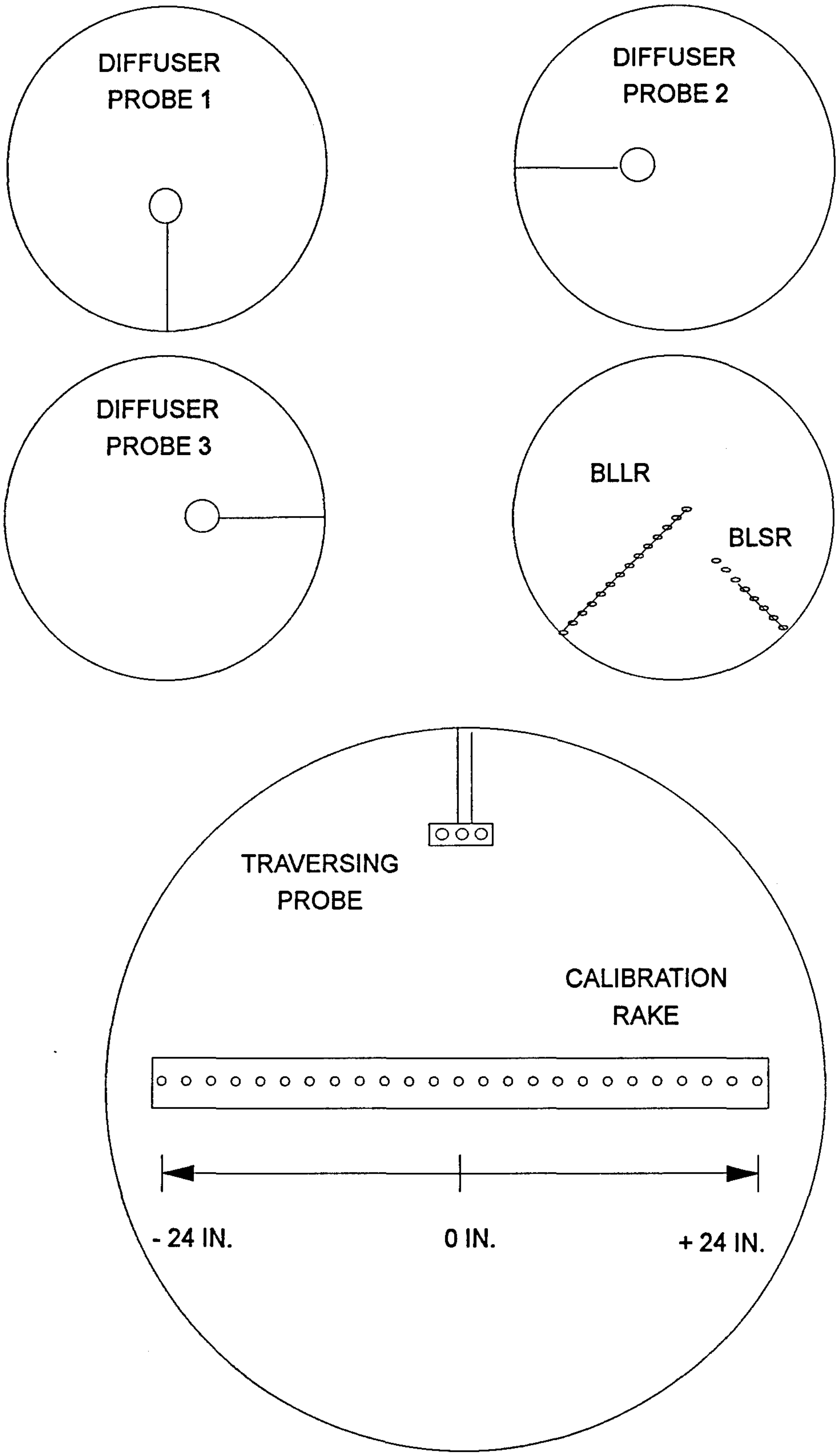


FIGURE 20. ORIENTATION OF CALIBRATION RAKE AND STRUT MOUNTED INSTRUMENTATION

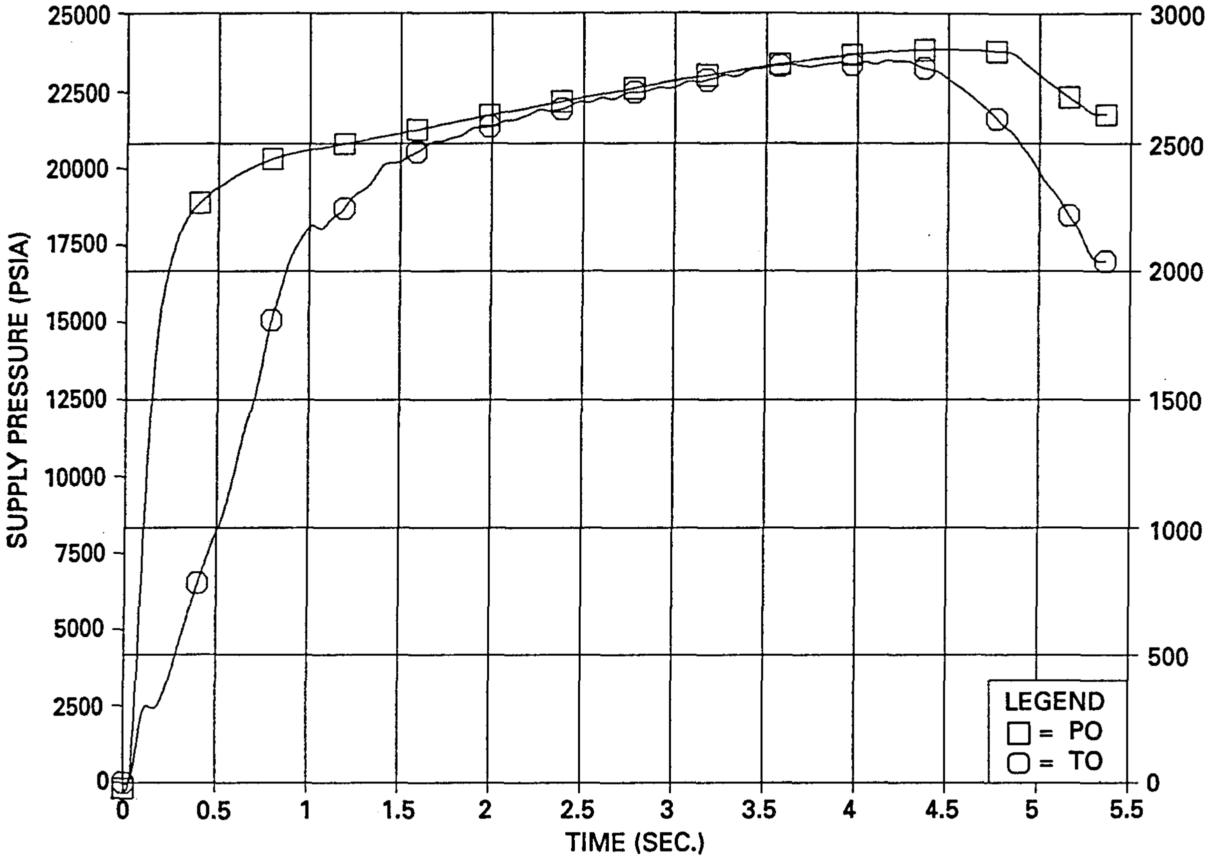


FIGURE 21. TYPICAL SUPPLY CONDITIONS FOR TUNNEL 9 HIGH MACH NUMBER OPERATION

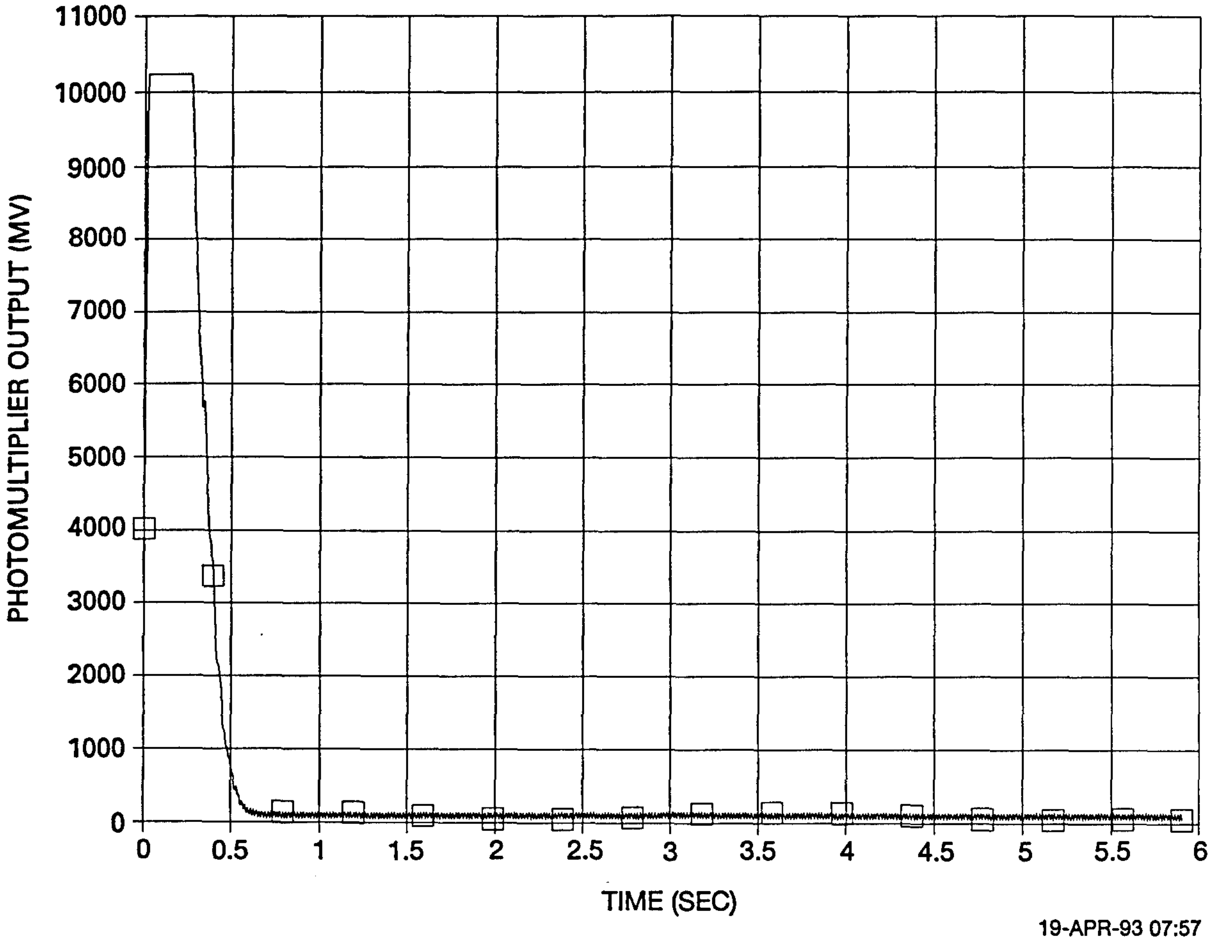


FIGURE 22. PHOTOMULTIPLIER SIGNAL VS. TIME

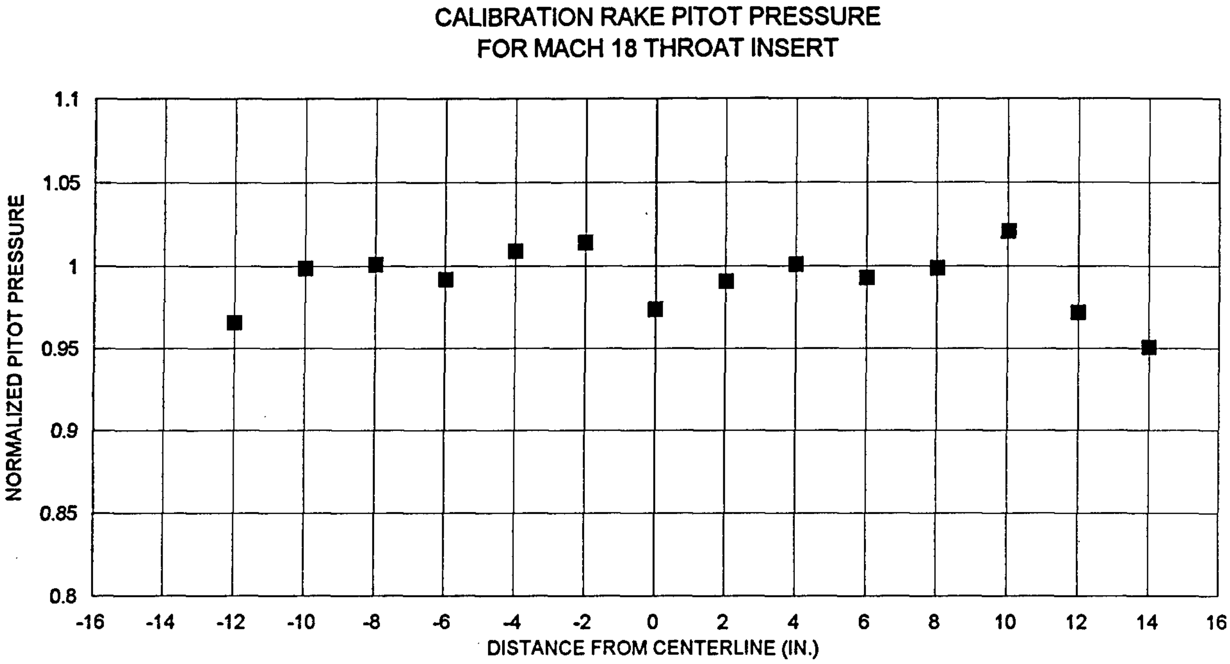


FIGURE 23. NORMALIZED PITOT PRESSURE VS. DISTANCE FROM CENTERLINE FOR RUN 2274

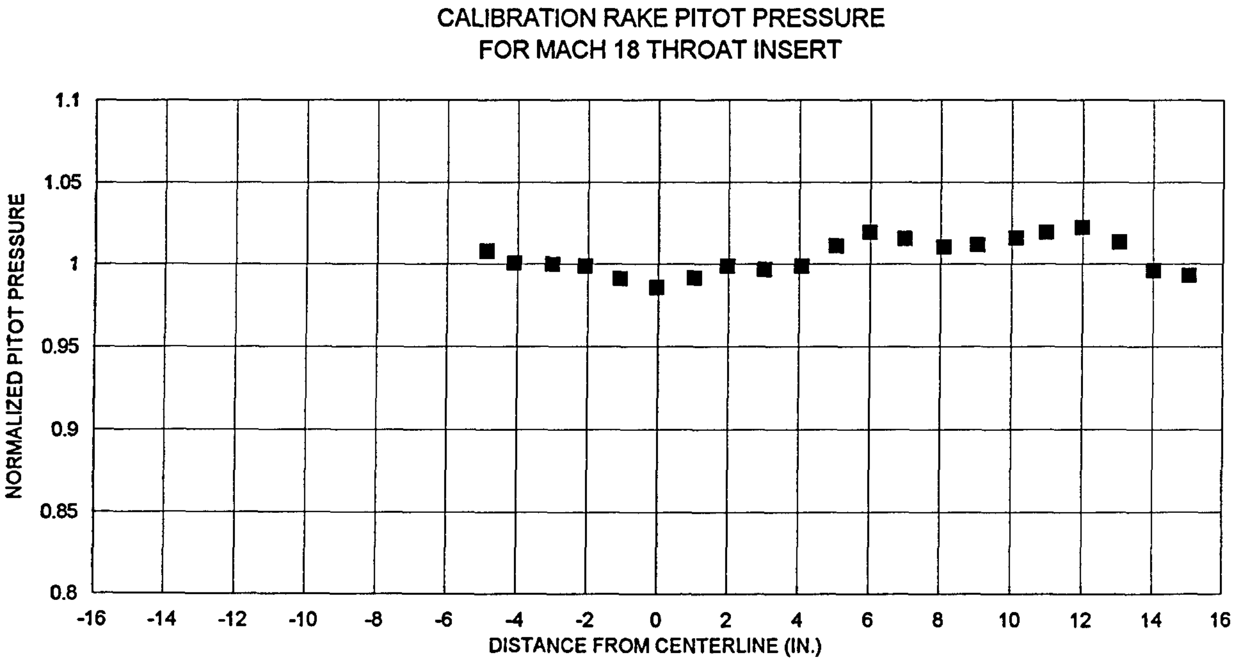


FIGURE 24. NORMALIZED PITOT PRESSURE VS. DISTANCE FROM CENTERLINE FOR RUN 2338

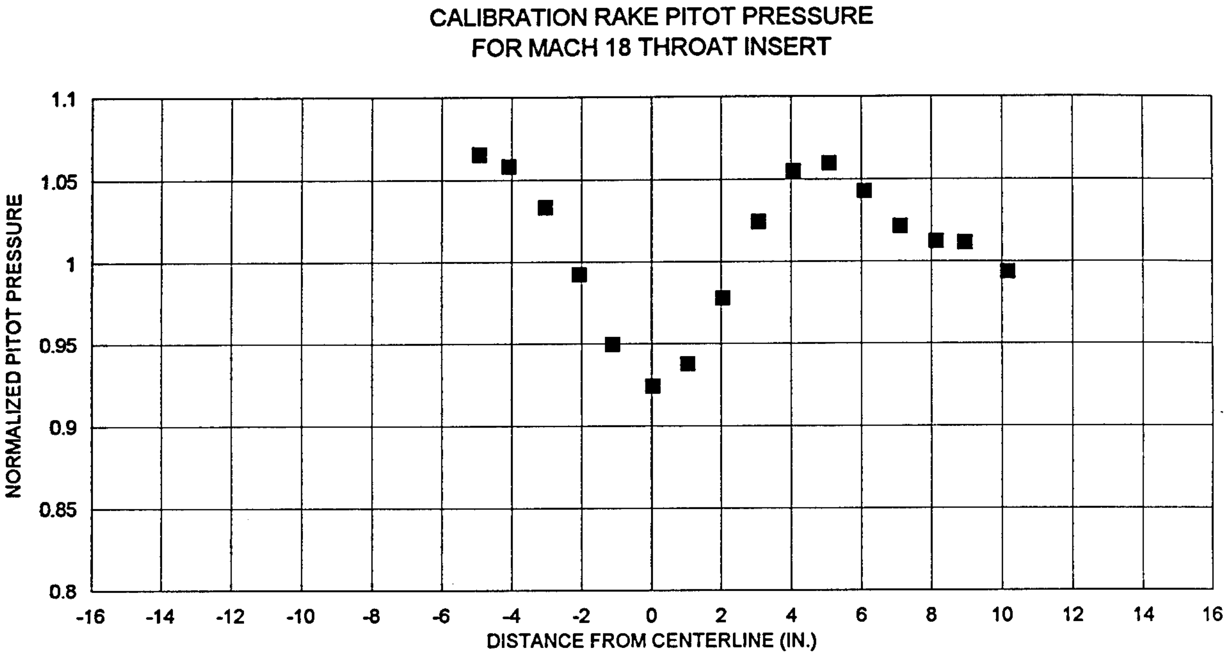


FIGURE 25. NORMALIZED PITOT PRESSURE VS. DISTANCE FROM CENTERLINE FOR RUN 2341

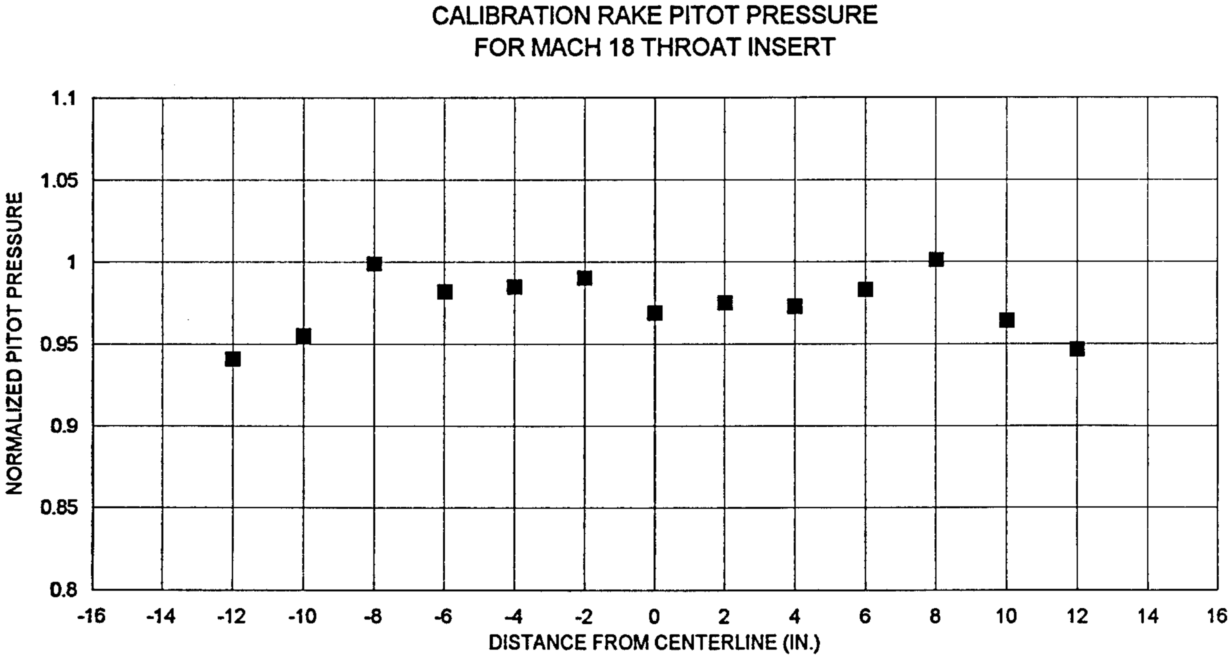


FIGURE 26. NORMALIZED PITOT PRESSURE VS. DISTANCE FROM CENTERLINE FOR RUN 2343

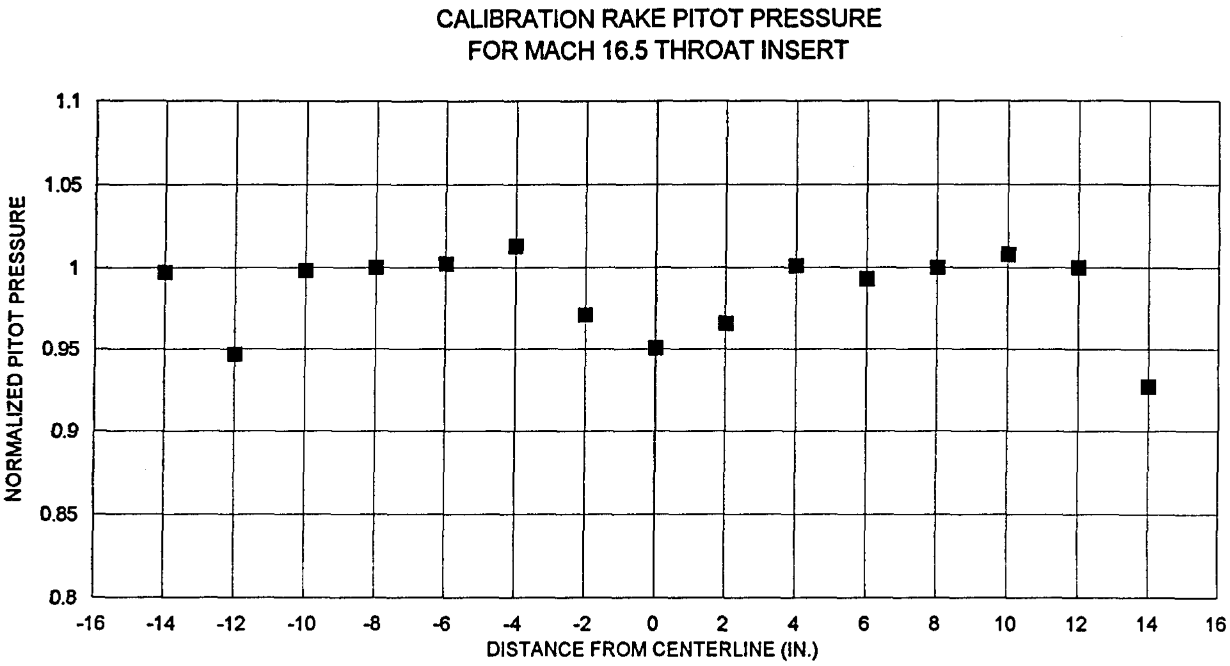


FIGURE 27. NORMALIZED PITOT PRESSURE VS. DISTANCE FROM CENTERLINE FOR RUN 2374

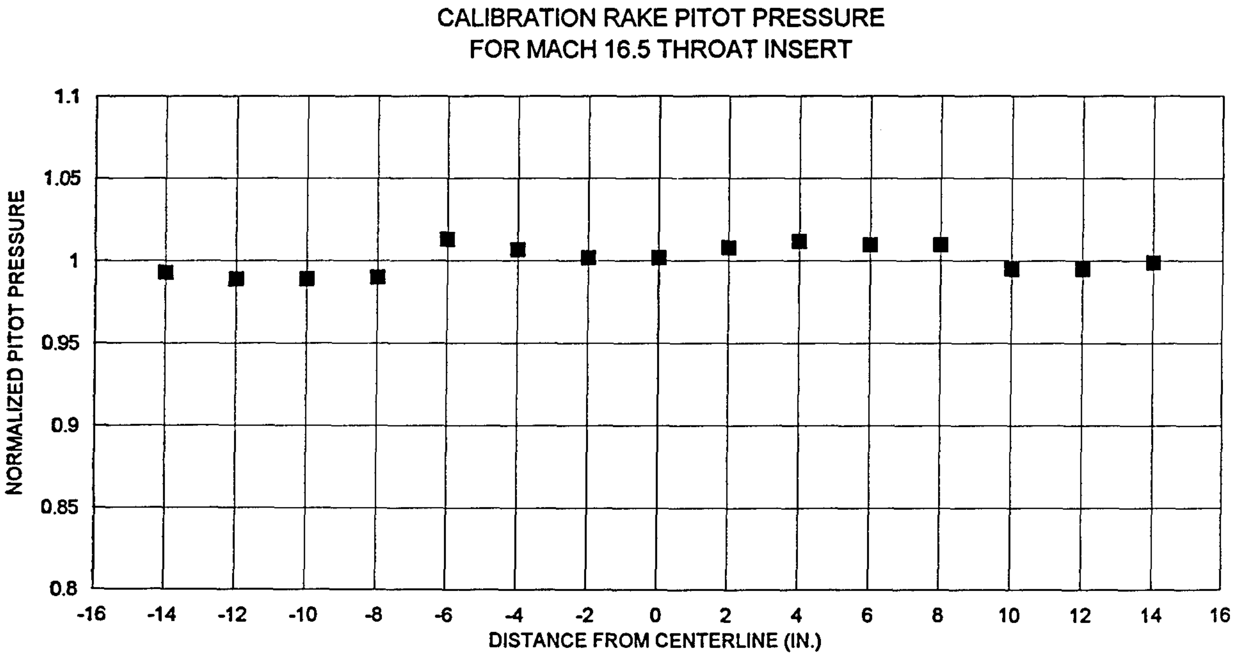


FIGURE 28. NORMALIZED PITOT PRESSURE VS. DISTANCE FROM CENTERLINE FOR RUN 2377

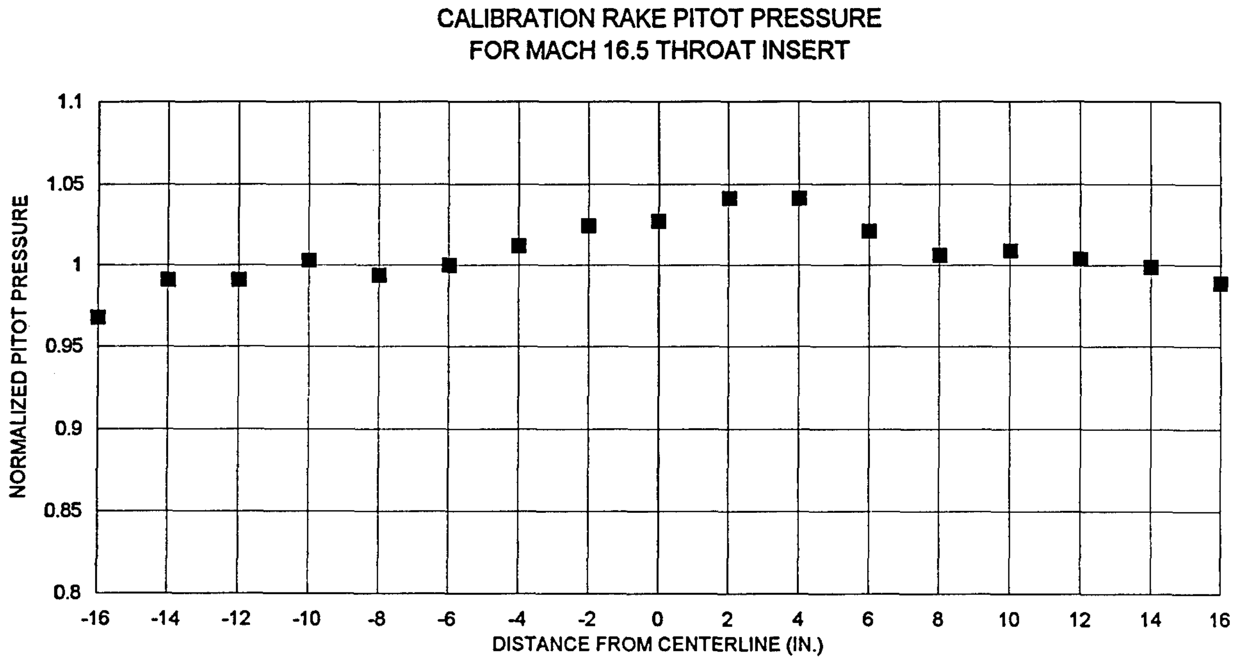


FIGURE 29. NORMALIZED PITOT PRESSURE VS. DISTANCE FROM CENTERLINE FOR RUN 2379

TABLE 1. HARDWARE SET THROAT DIAMETERS

HARDWARE SET	AS-BUILT MINIMUM THROAT DIAMETER (INCHES)
1	0.5262
2	0.5260
3	0.5275
3 (Modified)	0.6284
4	0.5273
5	0.5267
6	0.5521

TABLE 2. ESTIMATED UNCERTAINTIES

A. TUNNEL INSTRUMENTATION

Quantity	Type	Range	Nominal Value	B	P	U	$\frac{U}{\text{Nominal}}$
P_o (psia)	Viatran 214	50000	21060	73.453	10.422	± 74.188	± 0.35%
T_o (° F)	W5RE vs W26RE	4200	2765	14.806	0.749	± 14.825	± 0.54%
Pt (psia)	Kulite XCW-093	15	6.59	0.012	0.006	± 0.013	± 0.20%
Thetas (degrees)	Houston Sci (1150)	NA	NA	0.017	0.034	± 0.038	NA

B. MODEL INSTRUMENTATION

Quantity	Type	Range	Nominal Value	B	P	U	$\frac{U}{\text{Nominal}}$
9HV6-5 Force Balance							
FN (lb)		2000	317.2	7.923	0.626	± 7.948	± 2.5%
FY (lb)		1000	4.535	4.463	0.156	± 4.466	*
FA (lb)		600	93.4	0.059	0.102	± 0.118	± 0.13%
MX (in-lb)		800	0.623	0.26	0.154	± 0.302	*
MY (in-lb)		NA	139.3	12.802	1.518	± 12.892	± 9.25%
MZ (in-lb)		NA	-17.6	14.092	0.528	± 14.102	*
Pressures							
Rake Pitot Pressure (psia)	Kulite XCW-093	15	6.581	0.029	0.006	± 0.030	± 0.46%
Model Static Pressure (psia)	PTQH	5	3.655	0.01	0.008	± 0.013	± 0.36%
Base Pressure (psia)	PTQH	5	0.008	0.014	0.007	± 0.015	± 187%**
Temperature							
Surface Temp. Rise (°F)	Medtherm	NA	NA	1	1.303	± 1.642	NA
YTRAV (in)	NA	NA	NA	0.006	0.001	± 0.006	NA

* Due to model symmetry, the nominal values of these quantities are approximately zero.

** The 10 mmHg Baratron did not operate during the calibration phase of this run. The 1000 mmHg Baratron had to be used for calibration of base pressure gages.

TABLE 2. ESTIMATED UNCERTAINTIES (CONTINUED)

C. CALCULATED PARAMETERS

Parameter Units	Nominal Value	B	P	U	$\frac{U}{\text{Nominal}}$
Mach	16.35	0.019	3.723e-03	± 0.019	± 0.12%
P_∞ (psia)	0.019	6.439e-05	2.506e-05	± 6.910e-05	± 0.36%
Q_∞ (psia)	3.578	6.513e-03	3.256e-03	± 7.281e-03	± 0.20%
T_∞ (°F)	69.98	0.437	0.037	± 0.439	± 0.63%
Re_∞ (1/ft)	2.643e+06	2.232e+04	1.902e+03	± 2.240e+04	± 0.85%
Rho_∞ (lbm/ft^3)	7.122e-04	3.640e-06	6.758e-07	± 3.702e-06	± 0.52%
U_∞ (ft)	6820	16.28	0.834	± 16.31	± 0.24%
VIP ($\text{ft}^{1/2}$)	0.010	3.660e-05	4.998e-06	± 3.694e-05	± 0.37%
For Calibration Rake					
CP	1.834	8.016e-03	2.367e-03	± 8.358e-03	± 0.46%
P/P01	2.885e-04	1.992e-06	3.209e-07	± 2.018e-06	± 0.70%
P/P_∞	344.3	1.737	0.548	± 1.822	± 0.53%
P/Pt	0.999	4.352e-03	1.285e-03	± 4.538e-03	± 0.45%
For Cone Model					
CP	0.139	2.623e-03	2.240e-03	± 3.449e-03	± 2.48%
P/P01	2.258e-05	4.545e-07	3.510e-07	± 5.743e-07	± 2.54%
P/P_∞	26.94	0.483	0.42	± 0.640	± 2.38%
P/Pt	0.078	1.426e-03	1.216e-03	± 1.874e-03	± 2.4%
ST	0.015	NA	6.700e-04	± 6.700e-04	± 4.5 %
ALPHA (deg)	16.36	0.086	0.045	± 0.097	± 0.59%
AFC	0.166	4.661e-04	3.330e-04	± 5.728e-04	± 0.35%
CAFC	0.163	4.076e-03	2.052e-03	± 4.563e-03	± 2.80%

TABLE 2. ESTIMATED UNCERTAINTIES (CONTINUED)

C. CALCULATED PARAMETERS (CONTINUED)

Parameter Units	Nominal Value	B	P	U	$\frac{U}{\text{Nominal}}$
CPB	-2.926e-03	4.048e-03	2.024e-03	± 4.526e-03	±155%**
NFC	0.563	0.014	1.233e-03	± 0.014	± 2.49%
PMC	-0.022	7.684e-04	7.231e-05	± 7.718e-04	± 3.50%
RMC	1.887e-05	4.871e-05	4.829e-06	± 4.895e-05	*
YFC	8.051e-03	7.928e-03	3.647e-04	± 7.937e-03	*
YMC	-8.947e-04	5.644e-04	2.258e-05	± 5.649e-04	*
XCPP	0.706***	7.340e-04	8.299e-05	± 7.387e-04	± 0.10%
XCPY	0.778***	0.082	3.639e-03	± 0.082	± 10.54%

* Due to model symmetry, the nominal values of these quantities are approximately zero.

** The 10 mmHg Baratron did not operate during the calibration phase of this run. The 1000 mmHg Baratron had to be used for calibration of base pressure gages.

*** The F_Jitter program currently does not contain an input to reference the moment- reference-center to the nose. To get XCP referenced to the nose, add the value of XCPTERM (found in the data printout) to the jitter output value for XCPP and XCPY.

TABLE 3. RUN MATRIX

Run #	Nominal Mach #	Hardware Set	Core	Reynolds No. (1/ft)	Comments
2271	16.68	1	24 in.	1.6×10^6	Calibration rake. Station 1. Po = 12000 psia.
2272	17.4	1	24 in.	2.0×10^6	Calibration rake. Station 1. Po = 15000 psia.
2274	17.45	1	24 in.	2.13×10^6	Calibration rake. Station 1. Po = 20000 psia. Throat damaged near end of run.
2275	17.3	1	------	2.4×10^6	Calibration rake. Station 1. Damaged Throat.
2276	17.4	1	------	2.0×10^6	Calibration rake (rotated 180°). Station 1. Damaged Throat.
2293	17.1	1	------	2.3×10^6	Calibration rake. Station 1. Reworked throat.
2294	17.2	1	------	2.3×10^6	Calibration rake (vertical orientation). Station 1. Reworked throat.
2295	17.3	1	------	2.5×10^6	Calibration rake. Station 2. Reworked throat.
2299	14	--------	------	-------------	Diagnostics.
2300	14	--------	------	-------------	Diagnostics.
2301	14	--------	------	-------------	Diagnostics.
2302	14	--------	------	-------------	Diagnostics.
2303	14	--------	------	-------------	Diagnostics.
2304	14	--------	------	-------------	Diagnostics.
2305	17.2	1	------	-------------	Diagnostics.
2306	17.2	1	------	-------------	Diagnostics.
2307	17.2	1	------	-------------	Diagnostics.
2308	17.2	1	------	-------------	Diagnostics.

Model Position (inches from nozzle exit):
Station 1 = 24, Station 2 = 67, Station 3 = 110

TABLE 3. RUN MATRIX (CONTINUED)

Run #	Nominal Mach #	Hardware Set	Core	Reynolds No. (1/ft)	Comments
2309	14	1	------	-------------	Diagnostics Verification Run.
2338	18.25	2	30 in.	2.09×10^6	APL Inlet Model. 1st run after Mach 10.
2339	17.72	2	20 in.	2.54×10^6	APL inlet Model.
2340	17.69	2	20 in.	2.40×10^6	APL inlet Model.
2341	17.82	2	20 in.	2.50×10^6	APL inlet Model.
2343	17.69	2	20 in.	2.32×10^6	Calibration rake. Station 1.
2344	17.38	2	20 in.	2.27×10^6	Calibration rake. Station 2.
2345	17.54	2	24 in.	2.35×10^6	Calibration rake. Station 3. Flow not symmetric.
2346	17.56	2	16 in.	2.23×10^6	Calibration rake. Nozzle exit.
2347	17.39	3	20 in.	2.55×10^6	Calibration rake. Station 1.
2348	17.61	2	20 in.	2.37×10^6	Step insert. Station 1. Blow-by failure.
2349	17.64	2	20 in.	2.48×10^6	Repeat of 2343.
2350	17.68	2	20 in.	2.31×10^6	Traversing rake.
2352	17.58	2	20 in.	2.30×10^6	Calibration rake. Station 1. Quick ramp of Po and To. Diffuser probes added.
2353	17.47	2	20 in.	2.19×10^6	Calibration rake. Station 1. High To.
2354	14	NA	------	2.00×10^6	Calibration rake. Station 1. Diffuser study.
2358	17.45	2	20 in.	2.03×10^6	17.45

Model Position (inches from nozzle exit):
Station 1 = 24, Station 2 = 67, Station 3 = 110

TABLE 3. RUN MATRIX (CONTINUED)

Run #	Nominal Mach #	Hardware Set	Core	Reynolds No. (1/ft)	Comments
2370	18.01	2	28	2.09×10^6	Calibration rake. Station 1. Boundary layer rakes and tufts added. 1st run after Mach 8.
2371	18.68	2	18	3.21×10^6	Calibration rake. Station 1. Low To.
2372	17.61	2	20	2.32×10^6	Repeat of 2370.
2373	16.49	3-mod	24	2.61×10^6	Calibration rake. Station 1.
2374	16.59	3-mod	24	2.65×10^6	Repeat of 2373.
2375	17.25	6	26	2.51×10^6	Calibration rake. Station 1.
2376	17.35	6	24	2.55×10^6	Repeat of 2375.
2377	16.66	3-mod	28	2.58×10^6	Calibration rake. Station 2.
2378	17.63	3-mod	40	2.63×10^6	Calibration rake. Station 3. 1st run after heater dismantled for in-house study and heater element replaced.
2379	16.73	3-mod	30	2.54×10^6	Calibration rake. Station 3.
2385	16.56	3-mod	24	2.70×10^6	Blunt Cone.

Model Position (inches from nozzle exit):
Station 1 = 24, Station 2 = 67, Station 3 = 110

TABLE 4. TUNNEL 9 FLOW UNIFORMITY CALIBRATION FOR RUN 2274

WTR 1604, RUN 2274, STATION 24 inches

MACH = 17.45 P0 = 21948. psia T0 = 2867. degF PTAVG = 4.94 psia

NOMINAL FREESTREAM CONDITIONS

MACH	QINF psia	TINF degR	PINF psia	REINF 1/ft	UINF ft/sec	RHOINF lbm/ft3	VIP ft**1/2
17.45	2.684	63.8	1.26E-02	2.13E+06	6950.	5.15E-04	1.20E-02

PROFILES NORMALIZED TO NOMINAL

Probe #	Dist. from center (in)	PT	M	Q	T	P	RE	U	RHO	VIP
1	-24.00	0.259	1.317	0.259	0.581	0.149	0.439	1.003	0.257	1.988
2	-22.00	0.378	1.219	0.378	0.676	0.254	0.553	1.003	0.376	1.640
3	-20.00	0.516	1.144	0.516	0.766	0.394	0.668	1.002	0.514	1.400
4	-18.00	0.641	1.095	0.641	0.836	0.535	0.763	1.001	0.639	1.254
5	-16.00	0.731	1.066	0.731	0.882	0.644	0.827	1.001	0.730	1.173
6	-14.00	0.887	1.025	0.887	0.953	0.845	0.930	1.000	0.886	1.063
7	-12.00	0.966	1.007	0.966	0.986	0.953	0.979	1.000	0.966	1.018
8	-10.00	0.999	1.000	0.999	1.000	0.999	1.000	1.000	0.999	1.000
9*	-8.00	1.001	1.000	1.001	1.000	1.001	1.000	1.000	1.001	1.000
10	-6.00	0.992	1.002	0.992	0.997	0.988	0.995	1.000	0.992	1.004
11	-4.00	1.009	0.998	1.009	1.004	1.013	1.006	1.000	1.009	0.995
12	-2.00	1.014	0.997	1.014	1.006	1.020	1.008	1.000	1.014	0.993
13	0.00	0.974	1.005	0.974	0.989	0.963	0.984	1.000	0.973	1.014
14	2.00	0.991	1.002	0.991	0.996	0.987	0.994	1.000	0.991	1.005
15	4.00	1.001	1.000	1.001	1.000	1.001	1.001	1.000	1.001	1.000
16	6.00	0.993	1.001	0.993	0.997	0.990	0.996	1.000	0.993	1.004
17*	8.00	0.999	1.000	0.999	1.000	0.999	1.000	1.000	0.999	1.000
18	10.00	1.021	0.996	1.021	1.008	1.029	1.012	1.000	1.021	0.990
19	12.00	0.972	1.006	0.972	0.989	0.961	0.983	1.000	0.972	1.015
20	14.00	0.951	1.010	0.951	0.980	0.932	0.970	1.000	0.951	1.026
21	16.00	0.743	1.063	0.743	0.887	0.658	0.834	1.001	0.742	1.163
22	18.00	0.655	1.090	0.655	0.843	0.551	0.773	1.001	0.653	1.240
23	20.00	0.535	1.136	0.536	0.778	0.415	0.684	1.002	0.534	1.374
24	22.00	0.403	1.203	0.404	0.694	0.279	0.575	1.003	0.401	1.586
25	24.00	0.270	1.305	0.271	0.591	0.159	0.451	1.003	0.269	1.943

* - Averaged to determine PTAVG and nominal conditions.

TABLE 5. TUNNEL 9 FLOW UNIFORMITY CALIBRATION FOR RUN 2343

WTR 1604, RUN 2343, STATION 24 inches

MACH = 17.68 P0 = 23029. psia T0 = 2780. degF PTAVG = 5.02 psia

NOMINAL FREESTREAM CONDITIONS

MACH	QINF psia	TINF degR	PINF psia	REINF 1/ft	UINF ft/sec	RHOINF lbm/ft3	VIP ft**1/2
17.68	2.723	60.7	1.24E-02	2.30E+06	6869.	5.35E-04	1.17E-02

PROFILES NORMALIZED TO NOMINAL

Probe #	Dist. from center (in)	PT	M	Q	T	P	RE	U	RHO	VIP
1	-24.00	0.227	1.352	0.227	0.551	0.124	0.405	1.004	0.225	2.123
2	-22.00	0.339	1.246	0.339	0.647	0.218	0.517	1.003	0.337	1.733
3	-20.00	0.465	1.169	0.466	0.735	0.341	0.628	1.002	0.464	1.475
4	-18.00	0.586	1.115	0.586	0.806	0.471	0.722	1.002	0.584	1.313
5	-16.00	0.679	1.082	0.679	0.856	0.580	0.790	1.001	0.678	1.217
6	-14.00	0.745	1.062	0.745	0.888	0.661	0.836	1.001	0.744	1.161
7	-12.00	0.941	1.013	0.941	0.976	0.918	0.964	1.000	0.940	1.032
8	-10.00	0.955	1.010	0.955	0.982	0.937	0.972	1.000	0.954	1.024
9*	-8.00	0.999	1.000	0.999	1.000	0.999	0.999	1.000	0.999	1.001
10	-6.00	0.982	1.004	0.982	0.993	0.975	0.989	1.000	0.982	1.009
11	-4.00	0.985	1.003	0.985	0.994	0.980	0.991	1.000	0.985	1.007
12	-2.00	0.990	1.002	0.990	0.996	0.986	0.994	1.000	0.990	1.005
13	0.00	0.969	1.006	0.969	0.988	0.957	0.981	1.000	0.969	1.016
14	2.00	0.975	1.005	0.975	0.990	0.965	0.985	1.000	0.975	1.013
15	4.00	0.973	1.006	0.973	0.989	0.962	0.983	1.000	0.973	1.014
16	6.00	0.983	1.003	0.983	0.993	0.976	0.990	1.000	0.983	1.009
17*	8.00	1.001	1.000	1.001	1.000	1.001	1.001	1.000	1.001	0.999
18	10.00	0.964	1.008	0.964	0.985	0.949	0.978	1.000	0.963	1.019
19	12.00	0.947	1.011	0.947	0.978	0.926	0.967	1.000	0.947	1.028
20	14.00	0.786	1.050	0.787	0.908	0.713	0.864	1.001	0.785	1.130
21	16.00	0.702	1.075	0.703	0.868	0.608	0.807	1.001	0.701	1.197
22	18.00	0.617	1.104	0.617	0.823	0.507	0.745	1.001	0.615	1.278
23	20.00	0.501	1.151	0.501	0.757	0.378	0.656	1.002	0.499	1.421
24	22.00	0.376	1.221	0.376	0.675	0.252	0.551	1.003	0.374	1.644
25	24.00	0.253	1.323	0.253	0.575	0.144	0.433	1.003	0.251	2.011

* - Averaged to determine PTAVG and nominal conditions.

TABLE 6. TUNNEL 9 FLOW UNIFORMITY CALIBRATION FOR RUN 2374

WTR 1604, RUN 2374, STATION 24 inches

MACH = 16.35   P0 = 21060. psia   T0 = 2765. degF   PTAVG = 6.60 psia

NOMINAL FREESTREAM CONDITIONS

MACH	QINF psia	TINF degR	PINF psia	REINF 1/ft	UINF ft/sec	RHOINF lbm/ft3	VIP ft**1/2
16.35	3.583	70.0	1.92E-02	2.65E+06	6820.	7.13E-04	1.01E-02

PROFILES NORMALIZED TO NOMINAL

Probe #	Dist. from center (in)	PT	M	Q	T	P	RE	U	RHO	VIP
1	24.00	0.289	1.288	0.289	0.607	0.174	0.470	1.004	0.287	1.879
2	22.00	0.426	1.190	0.427	0.710	0.301	0.595	1.003	0.424	1.543
3	20.00	0.575	1.120	0.575	0.800	0.458	0.714	1.002	0.573	1.326
4	18.00	0.715	1.071	0.715	0.874	0.623	0.815	1.001	0.713	1.186
5	16.00	0.899	1.022	0.899	0.958	0.860	0.937	1.000	0.898	1.056
6	14.00	0.927	1.016	0.927	0.970	0.898	0.955	1.000	0.926	1.039
7	12.00	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
8	10.00	1.008	0.998	1.008	1.003	1.011	1.005	1.000	1.008	0.996
9*	8.00	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
10	6.00	0.993	1.001	0.993	0.997	0.990	0.996	1.000	0.993	1.004
11	4.00	1.001	1.000	1.001	1.000	1.001	1.001	1.000	1.001	1.000
12	2.00	0.966	1.007	0.966	0.986	0.952	0.979	1.000	0.966	1.018
13	0.00	0.951	1.010	0.951	0.980	0.931	0.970	1.000	0.950	1.026
14	-2.00	0.971	1.006	0.971	0.988	0.960	0.982	1.000	0.971	1.015
15	-4.00	1.013	0.997	1.012	1.005	1.018	1.008	1.000	1.013	0.994
16	-6.00	1.002	1.000	1.002	1.001	1.003	1.001	1.000	1.002	0.999
17*	-8.00	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
18	-10.00	0.998	1.000	0.998	0.999	0.997	0.999	1.000	0.998	1.001
19	-12.00	0.947	1.011	0.947	0.978	0.926	0.967	1.000	0.946	1.028
20	-14.00	0.911	1.019	0.911	0.963	0.876	0.945	1.000	0.910	1.049
21	-16.00	0.771	1.055	0.771	0.901	0.694	0.854	1.001	0.770	1.141
22	-18.00	0.654	1.091	0.654	0.843	0.550	0.772	1.001	0.652	1.241
23	-20.00	0.517	1.144	0.517	0.767	0.395	0.669	1.002	0.515	1.399
24	-22.00	0.379	1.219	0.379	0.677	0.255	0.554	1.003	0.377	1.638
25	-24.00	0.244	1.333	0.244	0.567	0.137	0.424	1.004	0.242	2.049

* - Averaged to determine PTAVG and nominal conditions.

TABLE 7. TUNNEL 9 FLOW UNIFORMITY CALIBRATION FOR RUN 2377

WTR 1604, RUN 2377, STATION 67 inches

MACH = 16.39   PO = 20625. psia   TO = 2750. degF   PTAVG = 6.38 psia

NOMINAL FREESTREAM CONDITIONS

MACH	QINF psia	TINF degR	PINF psia	REINF 1/ft	UINF ft/sec	RHOINF lbm/ft3	VIP ft**1/2
16.39	3.462	69.3	1.84E-02	2.59E+06	6799.	6.93E-04	1.02E-02

PROFILES NORMALIZED TO NOMINAL

Probe #	Dist. from center (in)	PT	M	Q	T	P	RE	U	RHO	VIP
1	24.00	0.278	1.298	0.278	0.598	0.165	0.459	1.004	0.276	1.916
2	22.00	0.398	1.207	0.398	0.690	0.273	0.571	1.003	0.396	1.597
3	20.00	0.539	1.135	0.539	0.780	0.418	0.686	1.002	0.537	1.370
4	18.00	0.764	1.057	0.764	0.897	0.684	0.849	1.001	0.762	1.147
5	16.00	0.899	1.022	0.899	0.958	0.861	0.937	1.000	0.899	1.056
6	14.00	0.999	1.000	0.999	1.000	0.999	1.000	1.000	0.999	1.000
7	12.00	0.995	1.001	0.995	0.998	0.992	0.997	1.000	0.995	1.003
8	10.00	0.995	1.001	0.995	0.998	0.993	0.997	1.000	0.995	1.002
9*	8.00	1.010	0.998	1.010	1.004	1.014	1.006	1.000	1.010	0.995
10	6.00	1.010	0.998	1.010	1.004	1.015	1.006	1.000	1.010	0.995
11	4.00	1.012	0.998	1.012	1.005	1.017	1.007	1.000	1.012	0.994
12	2.00	1.008	0.998	1.008	1.003	1.012	1.005	1.000	1.009	0.996
13	0.00	1.002	1.000	1.002	1.001	1.002	1.001	1.000	1.002	0.999
14	-2.00	1.002	1.000	1.002	1.001	1.003	1.001	1.000	1.002	0.999
15	-4.00	1.007	0.999	1.007	1.003	1.010	1.004	1.000	1.007	0.997
16	-6.00	1.013	0.997	1.013	1.005	1.018	1.008	1.000	1.013	0.994
17*	-8.00	0.990	1.002	0.990	0.996	0.986	0.994	1.000	0.990	1.005
18	-10.00	0.989	1.002	0.989	0.995	0.984	0.993	1.000	0.989	1.006
19	-12.00	0.989	1.002	0.989	0.996	0.985	0.994	1.000	0.989	1.005
20	-14.00	0.993	1.001	0.993	0.997	0.990	0.996	1.000	0.993	1.004
21	-16.00	0.868	1.030	0.868	0.944	0.819	0.917	1.001	0.867	1.075
22	-18.00	0.717	1.071	0.717	0.874	0.625	0.816	1.001	0.715	1.185
23	-20.00	0.500	1.152	0.500	0.757	0.377	0.656	1.002	0.498	1.423
24	-22.00	0.373	1.223	0.373	0.672	0.249	0.548	1.003	0.371	1.652
25	-24.00	0.244	1.333	0.244	0.567	0.138	0.424	1.004	0.243	2.047

* - Averaged to determine PTAVG and nominal conditions.

TABLE 8. TUNNEL 9 FLOW UNIFORMITY CALIBRATION FOR RUN 2379

WTR 1604, RUN 2379, STATION 110 inches

MACH = 16.73 PO = 21123. psia TO = 2728. degF PTAVG = 5.96 psia

NOMINAL FREESTREAM CONDITIONS

MACH	QINF psia	TINF degR	PINF psia	REINF 1/ft	UINF ft/sec	RHOINF lbm/ft3	VIP ft**1/2
16.73	3.236	66.1	1.65E-02	2.54E+06	6783.	6.51E-04	1.05E-02

PROFILES NORMALIZED TO NOMINAL

Probe #	Dist. from center (in)	PT	M	Q	T	P	RE	U	RHO	VIP
1	24.00	0.308	1.272	0.308	0.622	0.190	0.488	1.003	0.306	1.821
2	22.00	0.451	1.176	0.452	0.726	0.326	0.616	1.002	0.449	1.499
3	20.00	0.692	1.078	0.692	0.862	0.595	0.799	1.001	0.690	1.207
4	18.00	0.907	1.020	0.907	0.962	0.872	0.942	1.000	0.907	1.051
5	16.00	0.989	1.002	0.989	0.996	0.985	0.993	1.000	0.989	1.006
6	14.00	0.999	1.000	0.999	1.000	0.999	1.000	1.000	0.999	1.000
7	12.00	1.004	0.999	1.004	1.002	1.006	1.002	1.000	1.004	0.998
8	10.00	1.009	0.998	1.009	1.003	1.012	1.005	1.000	1.009	0.996
9*	8.00	1.006	0.999	1.006	1.002	1.009	1.004	1.000	1.006	0.997
10	6.00	1.021	0.996	1.021	1.008	1.030	1.013	1.000	1.021	0.989
11	4.00	1.041	0.992	1.041	1.016	1.059	1.025	1.000	1.042	0.980
12	2.00	1.041	0.992	1.041	1.016	1.058	1.025	1.000	1.041	0.980
13	0.00	1.027	0.994	1.027	1.011	1.039	1.017	1.000	1.028	0.986
14	-2.00	1.024	0.995	1.024	1.010	1.034	1.015	1.000	1.024	0.988
15	-4.00	1.012	0.998	1.012	1.005	1.017	1.007	1.000	1.012	0.994
16	-6.00	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
17*	-8.00	0.994	1.001	0.994	0.998	0.991	0.996	1.000	0.994	1.003
18	-10.00	1.003	0.999	1.003	1.001	1.004	1.002	1.000	1.003	0.999
19	-12.00	0.991	1.002	0.991	0.996	0.988	0.995	1.000	0.991	1.005
20	-14.00	0.991	1.002	0.991	0.996	0.987	0.994	1.000	0.991	1.005
21	-16.00	0.968	1.007	0.968	0.987	0.956	0.981	1.000	0.968	1.017
22	-18.00	0.882	1.026	0.883	0.951	0.838	0.927	1.000	0.882	1.066
23	-20.00	0.628	1.100	0.628	0.829	0.519	0.753	1.002	0.626	1.267
24	-22.00	0.384	1.216	0.384	0.680	0.260	0.558	1.003	0.382	1.627
25	-24.00	0.242	1.335	0.242	0.565	0.136	0.422	1.004	0.240	2.056

* - Averaged to determine PTAVG and nominal conditions.

TABLE 9. NOMINAL TEST CELL AND SUPPLY CONDITIONS FOR MACH 16.5

Freestream Mach	16.35
Freestream Reynolds No.	2.65 E06 /ft.
Supply Pressure	21060 psia
Supply Temperature	3225° R
Pitot Pressure	6.59 psia
Dynamic Pressure	3.58 psia
Freestream Pressure	0.019 psia
Freestream Temperature	70° R
Freestream Density	0.00071 lb/ft^3
Freestream Velocity	6820 ft/sec
Degrees Supercooled	15° R
Run Time	3 - 3.5 seconds

TABLE 10. NOMINAL TEST CELL AND SUPPLY CONDITIONS FOR MACH 18

Freestream Mach	17.64
Freestream Reynolds No.	2.48 E06 /ft.
Supply Pressure	22770 psia
Supply Temperature	3120° R
Pitot Pressure	5.02 psia
Dynamic Pressure	2.71 psia
Freestream Pressure	0.013 psia
Freestream Temperature	58.6° R
Freestream Density	0.11156 lb/ft^3
Dreestream Velocity	6640 ft/sec
Degrees Supercooled	24° R
Run Time	3 - 3.5 seconds

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GLOSSARY

a	Velocity of the local speed of sound, ft/sec.
ALPHA	Angle of attack, deg.
AFC	Axial force coefficient.
CAFC	Corrected axial force coefficient.
CP	Pressure coefficient.
CPB	Base pressure coefficient.
c_p	Specific heat at constant pressure.
c_v	Specific heat at constant volume.
FA	Axial force, lb.
FN	Normal force, lb.
FY	Yaw force, lb.
M, MACH	Free-stream Mach number, Mach = $U\infty/a$.
MX	Rolling moment, in-lb.
MY	Pitching moment, in-lb.
MZ	Yawing moment, in-lb.
NFC	Normal force coefficient.
P, $P\infty$	Free-stream static pressure, psia.
PMC	Pitching moment coefficient.
PTAVG	Average Pitot pressure, psia.
P_o	Tunnel supply pressure, psia.
P_{01}	Tunnel equivalent -perfect-gas supply pressure, psia.
Pt	Pitot pressure, psia.
Q, $Q\infty$	Free-stream dynamic pressure, psia.
Re, $Re\infty$	Free-stream Reynolds number, 1/ft.
Rho, $Rho\infty$	Free-stream density, lbm/ft^3.
RMC	Rolling moment coefficient.
ST	Stanton number.
T, $T\infty$	Free-stream static temperature, °F or °R.
ThetaS	Pitch angle of model support system, degrees.
T_o	Supply temperature, °F.
T_{oA}	Supply temperature thermocouple A, °F.
T_{oB}	Supply temperature thermocouple B, °F.
U, $U\infty$	Free-stream velocity, ft/sec.
VIP	Viscous interaction parameter $[M/(Re^{1/2})]$, $ft^{1/2}$.
XCPP	Pitch center of pressure, fraction of model length aft of nose.
XCPY	Yaw center of pressure, fraction of model length aft of nose.
YFC	Yaw force coefficient .
YMC	Yawing moment coefficient.
YTRAV	Traversing probe distance from tunnel centerline, in.
γ	Ratio of specific heats, c_p/c_v.

APPENDIX A

DIAGNOSTIC MACH 18 RUNS

The first run on hardware set 2 produced an unexpected flow profile. This run had a higher Mach number, a larger core size and smaller deviations in flow properties. A series of runs were made to resolve this anomaly. A number of possible causes for the anomaly were identified. Each of these factors and the tests run to determine their impact on flow quality are described below.

EFFECT OF THROAT HARDWARE CONTOUR CHANGES

The first theory to explain the flow anomalies focussed on changes to throat contours. As discussed earlier, the throat contour changes during the initial runs on a new set of hardware. These changes result from the high operating temperatures and long run times associated with Tunnel 9.

NEW THROAT

Since the NASP model was in place for run 2338 there was no calibration rake data obtained for the first four runs on hardware set 2. Since the largest throat contour change occurs during the first run, it was decided to use run 2347 as a calibration run in the first window station using hardware set 3. This was the first run on this set of hardware. Data is shown in Figure A-1 and Table A-1. Although the flow profile was comparable to run 2343, it did not repeat as well as expected. The profile for run 2343 has smaller deviations of -4.5 percent to +0.1 percent as compared to the deviations for run 2347 that are -13.0 percent to +0.3 percent. Since the throat of hardware set 2 had already taken its set in contour it was decided to return to set 2.

STEP INSERT

As the throat contour changes during the initial runs on the hardware, a discontinuity develops between the throat piece and the screwed insert (parts 2 and 3 in Figure A-2). To determine if this step could appreciably alter the flow profile run 2348 was made with an insert designed to eliminate the step (Figure A-3). The calibration data indicates that the flow profile was unaffected by the insert

Runs 2347 (first run on throat 3)and 2348 (throat 2 with step insert) were more repeatable with one another than with the nominal run (2343). Run 2349 was intended to be a repeat of run 2343. It was observed that the flow in run 2349 repeated the profile observed in run 2347 rather than that of run 2343. Data is shown in Figure A-4 and Table A-2. The Pitot pressure deviations are -10.8 percent to +6.5 percent.

From these runs it was determined that run 2343 had been an anomaly similar to run 2338. Although measurable dimensional changes are present, they do not alter the flow profile appreciably. Considering these results along with the results from runs 2347 to 2349, evidently the anomaly was not attributable to changes in throat contour.

EFFECT OF BLOCKAGE

Blockage was the next issue investigated to explain the anomalies observed. If tunnel blockage were occurring, it could cause the flow to separate from the tunnel walls thus reducing the core size and changing the flow profile. It is also possible that blocked flow could change the character of the flow in the diffuser section. To examine the blockage issue a run was made with an essentially empty tunnel and probes were installed to check the performance of the diffuser.

RUNNING WITH A CLEAR TUNNEL

For run 2350 the calibration rake was removed and all test cell windows were replaced with blank inserts contoured to match the test cell curvature. The sector blade was lowered beneath the test cell and the slots leading to the test cell under carriage were covered. The only flow disturbances were the vertically traversing rake and two strut mounted Pitot probes. The measurements from the traversing rake revealed a flow profile similar to that of run 2349 with a 20-inch core.

DIFFUSER EFFICIENCY

Cone static probes were installed in the tunnel diffuser pipe before run 2352 to investigate the diffuser efficiency. For comparison, diffuser data were acquired at Mach 14 with a Reynolds number of two million per foot. The diffuser data matched very well. A sharp cone was installed for run 2358 to change the flow profile entering the diffuser. Again, the Mach 18 diffuser data agreed with the Mach 14 diffuser data and no correlations were found.

Later in this program, another run (2370) repeated the anomalous runs. Data from this run is contained in Figure A-5 and Table A-3. The profile has a core of approximately 28 inches and variations in flow properties of -7.0 percent to +0.8 percent. Diffuser probe data from this anomalous run was compared to a run that had a smaller core and larger deviations in flow properties (run 2372). Figure A-6 shows the ratio of Pitot pressure to static pressure from one probe for these runs. Clearly the diffuser probe is unaffected by the phenomenon causing the anomaly. The other diffuser probes showed this same trend. From this data it was determined that the flow anomaly is not related to diffuser operation.

In terms of blockage, the tunnel start-up process behaved as expected. The data showed that the tunnel was not suffering from blockage or hard starts during the Mach 18 runs.

BOUNDARY-LAYER STATE

The state of the boundary layer was investigated to determine if it could be producing the anomalies observed. The issues examined were possible separation and relaminarization. Thermocouples were installed along the nozzle wall to obtain heat transfer data. Boundary layer rakes and fluorescent microtufts were added prior to run 2370. Computational Fluid Dynamics (CFD) analysis confirmed that the heat transfer data indicated a turbulent boundary layer along the length of the nozzle for all Mach 18 runs.

Figure A-7 displays representative Pitot pressure data from a boundary layer rake. Figure A-8 is a photograph of a section of the test cell wall with microtufts applied. The pressure measurements and flow visualization showed no localized regions of separation.

INVESTIGATION OF START-UP PROCESS

Two different theories were developed concerning the supply conditions during the tunnel start-up phase. One theory dealt with higher supply temperatures while the other involved lower supply temperatures. Each of these will be addressed separately.

HIGHER SUPPLY TEMPERATURES

Early in the tunnel start-up process the flow is in a condensed state as it is expanding. The flow eventually crosses over the experimental condensation onset curve into a noncondensed state. This process is illustrated in the pressure temperature diagram of Figure A-9. The data shown is from run 2349. The arrows indicate the direction for increasing time. The data points are equally spaced in time. The saturation line and experimental onset curve are also shown. The traces of supply conditions from run 2338 indicate that perhaps the flow had slightly more energy available in this critical start-up phase to push the flow into the noncondensed region and more fully expand. To accelerate the tunnel starting process and increase the available energy, runs 2352 and 2353 were made with higher supply conditions. However, these flow profiles did not repeat the flow profile observed during run 2338.

LOWER SUPPLY TEMPERATURES

Typical calibration rake data shows that approximately 0.8 seconds after tunnel start, the flow snaps into a profile with a 30-inch core and a nominal Mach number of 19. This profile lasts for approximately 0.3 seconds. The flow then snaps into a profile with a 20-inch core and a nominal Mach number of 17.5 for the remainder of the run. During the start-up process the supply conditions are ramping up to the required run conditions. During the period of Mach 19 flow the supply temperature has not yet reached it's full running level. Run 2371 was made to investigate the effect of low supply temperature on the flow profile. Not surprisingly, the data showed that the flow profile worsened with decreasing supply temperature.

OVERSIZED CONTOUR

The oversized contour of hardware set 6 was tested during run 2375. The profile is different from that of the other Mach 18 sets. The core size is approximately 26 inches while the Pitot pressure is 5.26 psia with a deviation of -4.8 percent to +1.6 percent as shown in Figure A-10 and Table A-4. The flow profile of run 2375 was duplicated with run 2376. The profile had very sharp corners at the boundary layer that is not typical of flow in Tunnel 9. The flow produced by modified set 3 seemed more consistent with the typical shape observed in Tunnel 9 at lower Mach numbers and no further testing was conducted with hardware set 6.

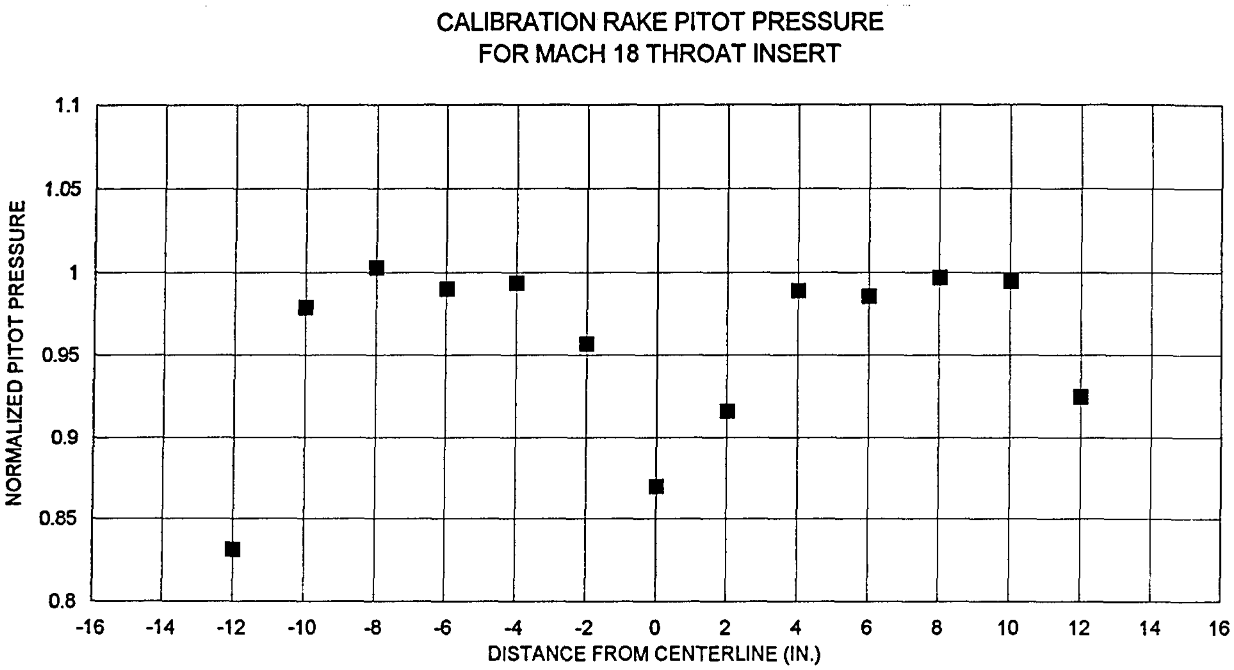

FIGURE A-1. NORMALIZED PITOT PRESSURE VS. DISTANCE FROM CENTERLINE FOR RUN 2347

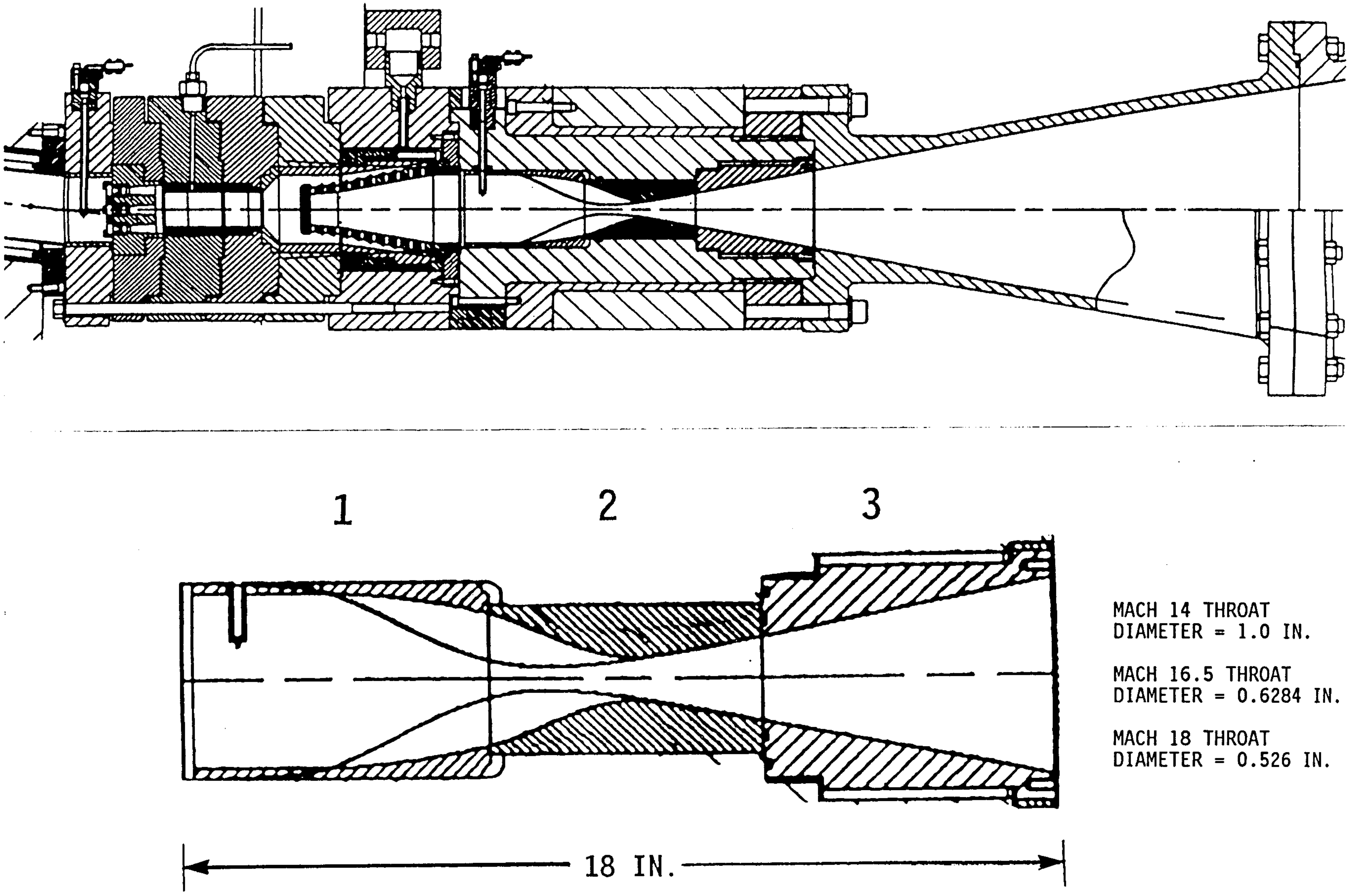

FIGURE A-2. MACH 14 NOZZLE THROAT SECTION WITH MACH 18 INSERT

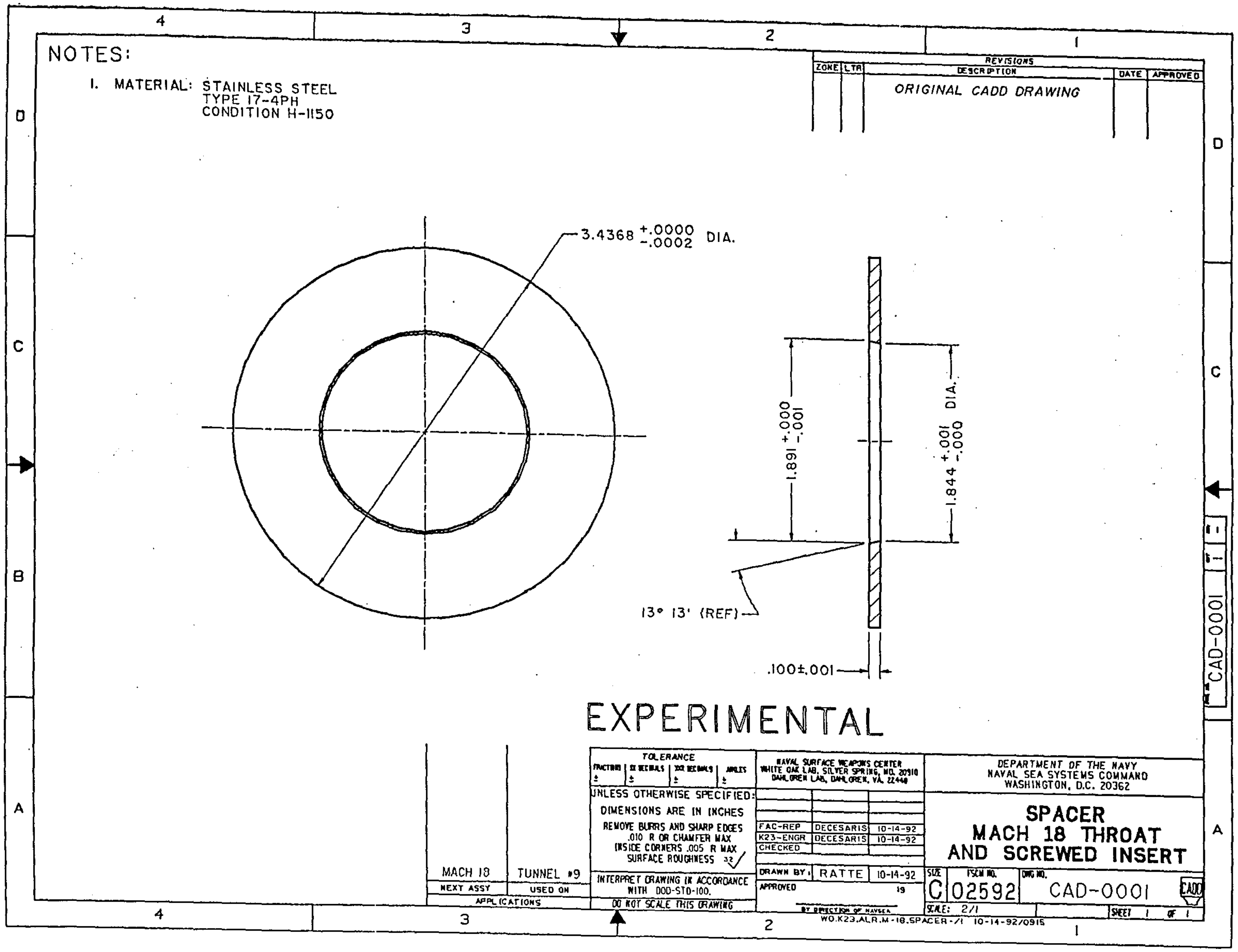

FIGURE A-3. MACH 18 STEP INSERT HARDWARE

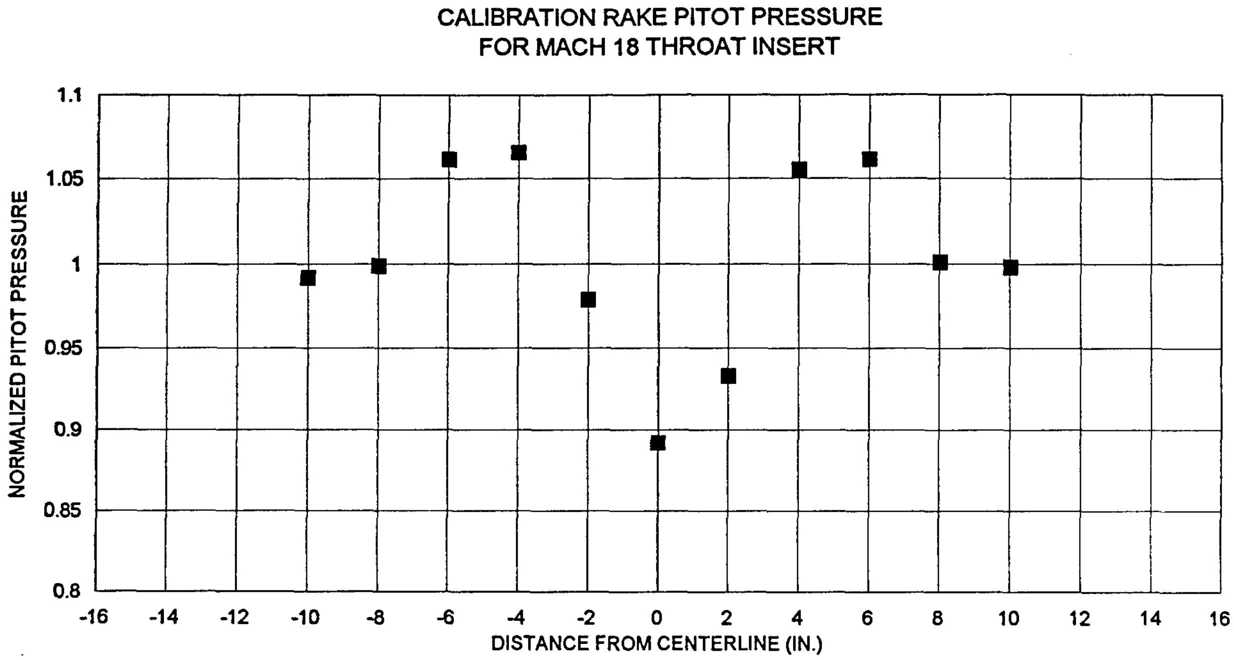

FIGURE A-4. NORMALIZED PITOT PRESSURE VS. DISTANCE FROM CENTERLINE FOR RUN 2349

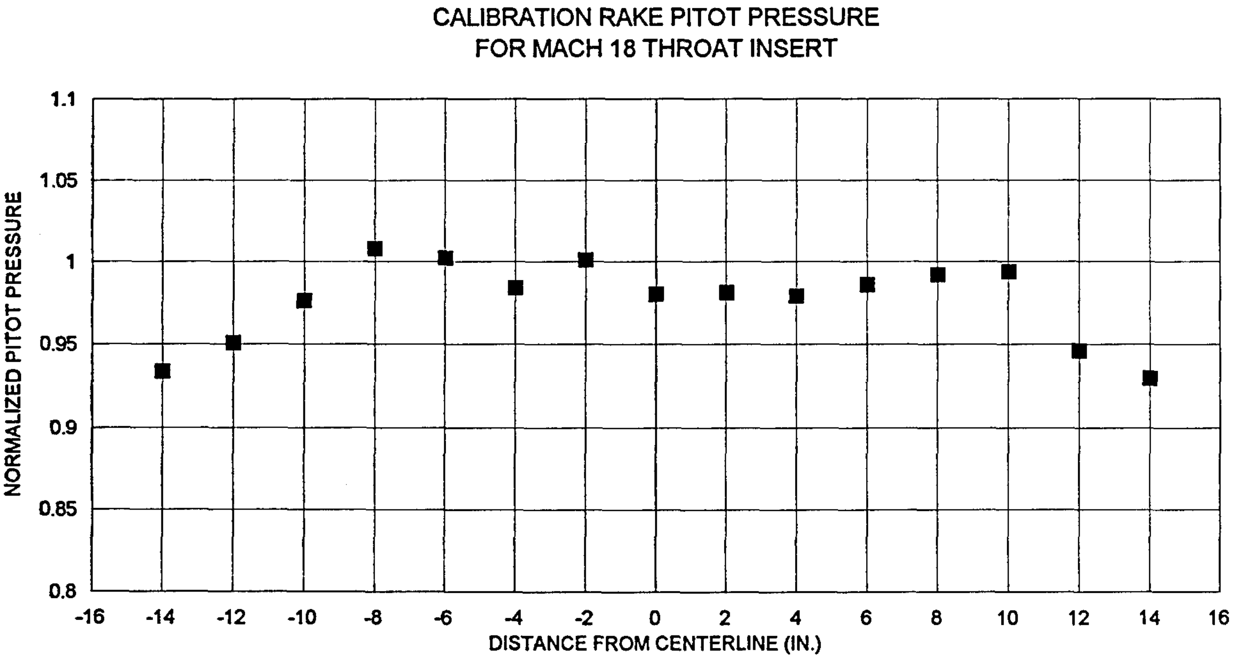

FIGURE A-5. NORMALIZED PITOT PRESSURE VS. DISTANCE FROM CENTERLINE FOR RUN 2370

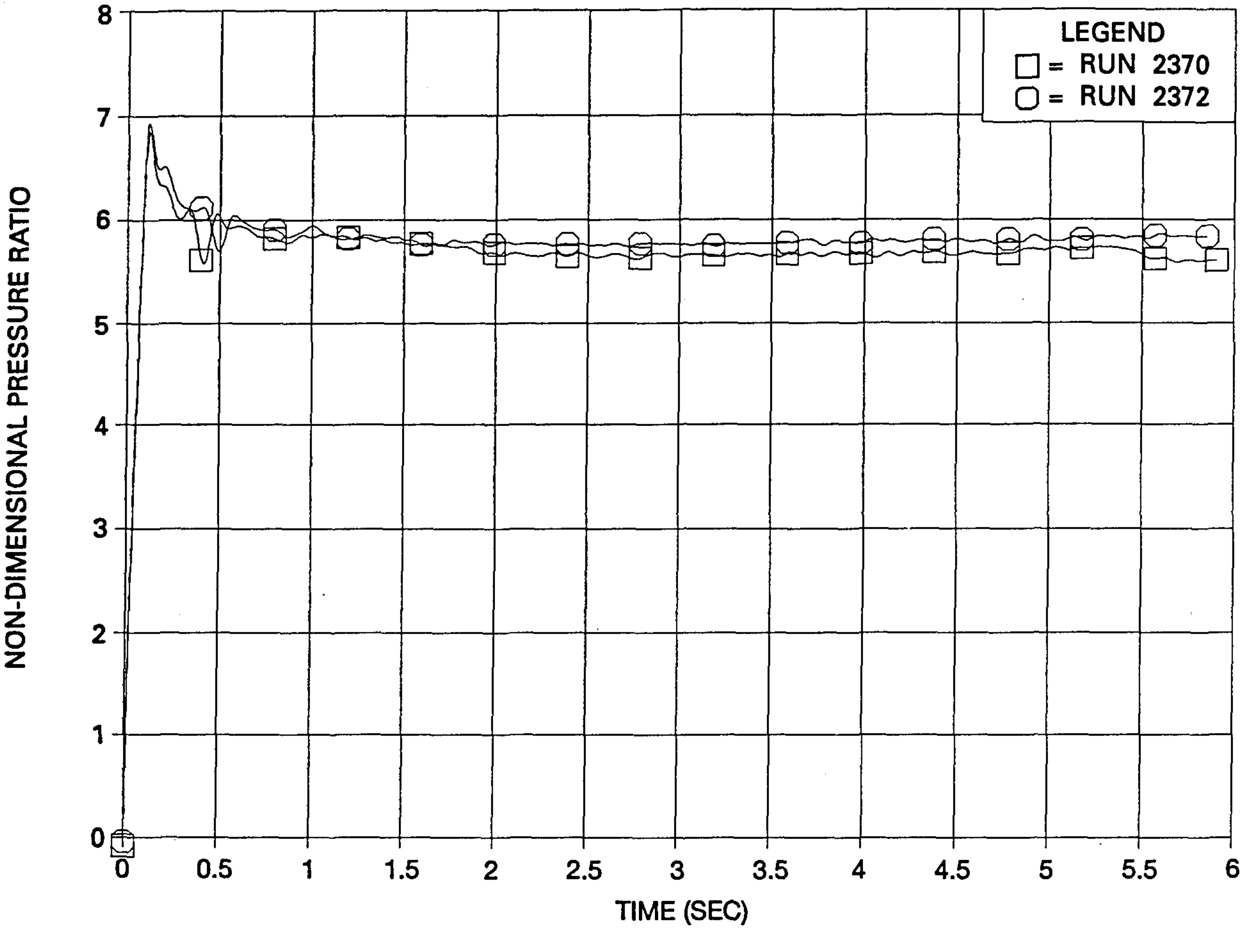

FIGURE A-6. DIFFUSER PROBE DATA

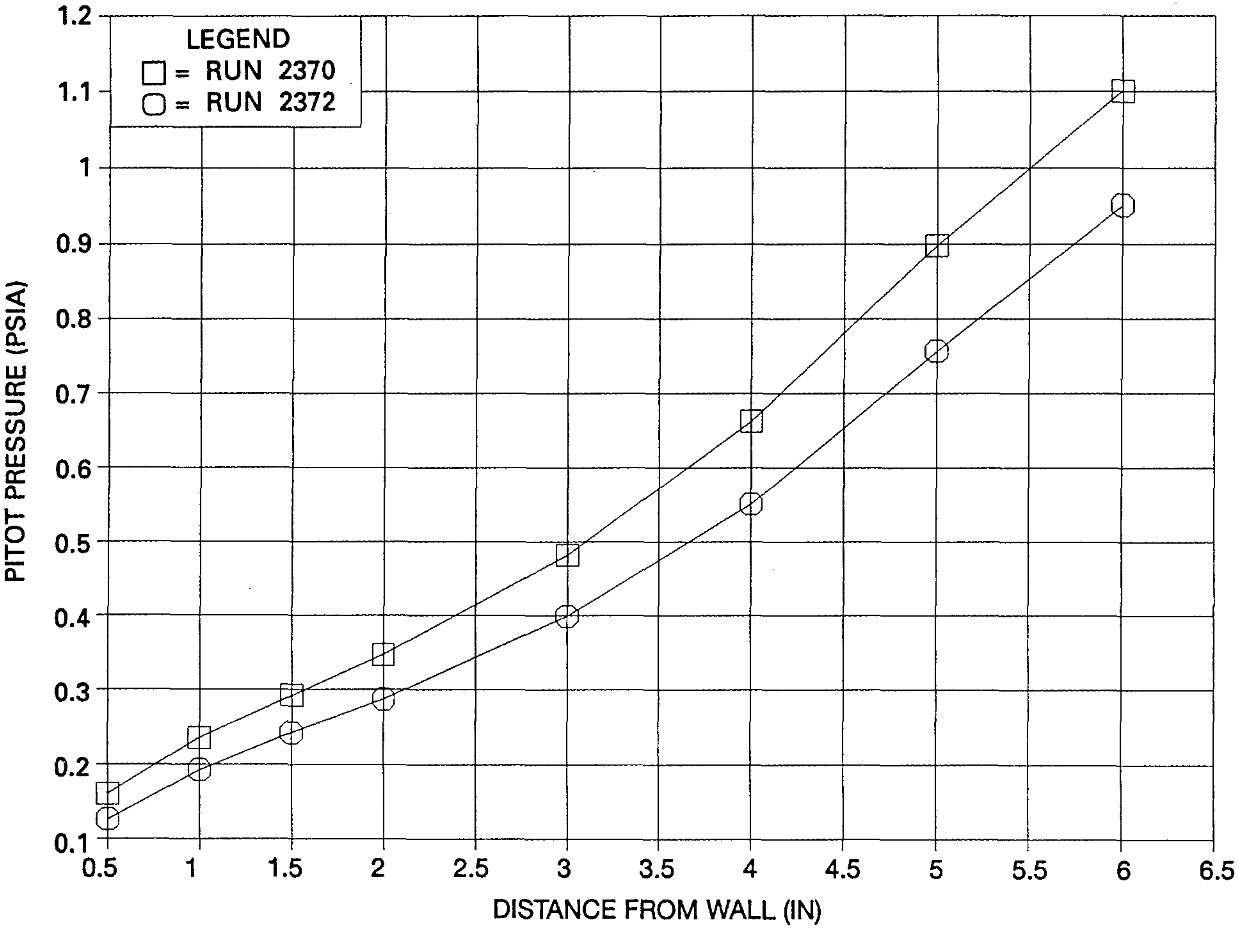

FIGURE A-7. BOUNDARY LAYER PITOT DATA

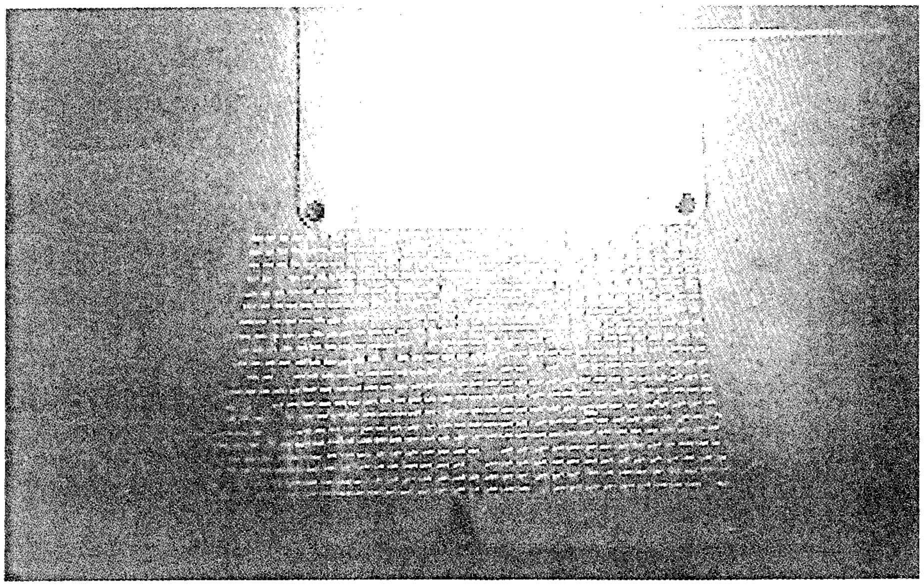

FIGURE A-8. PHOTOGRAPH OF MICROTUFTS

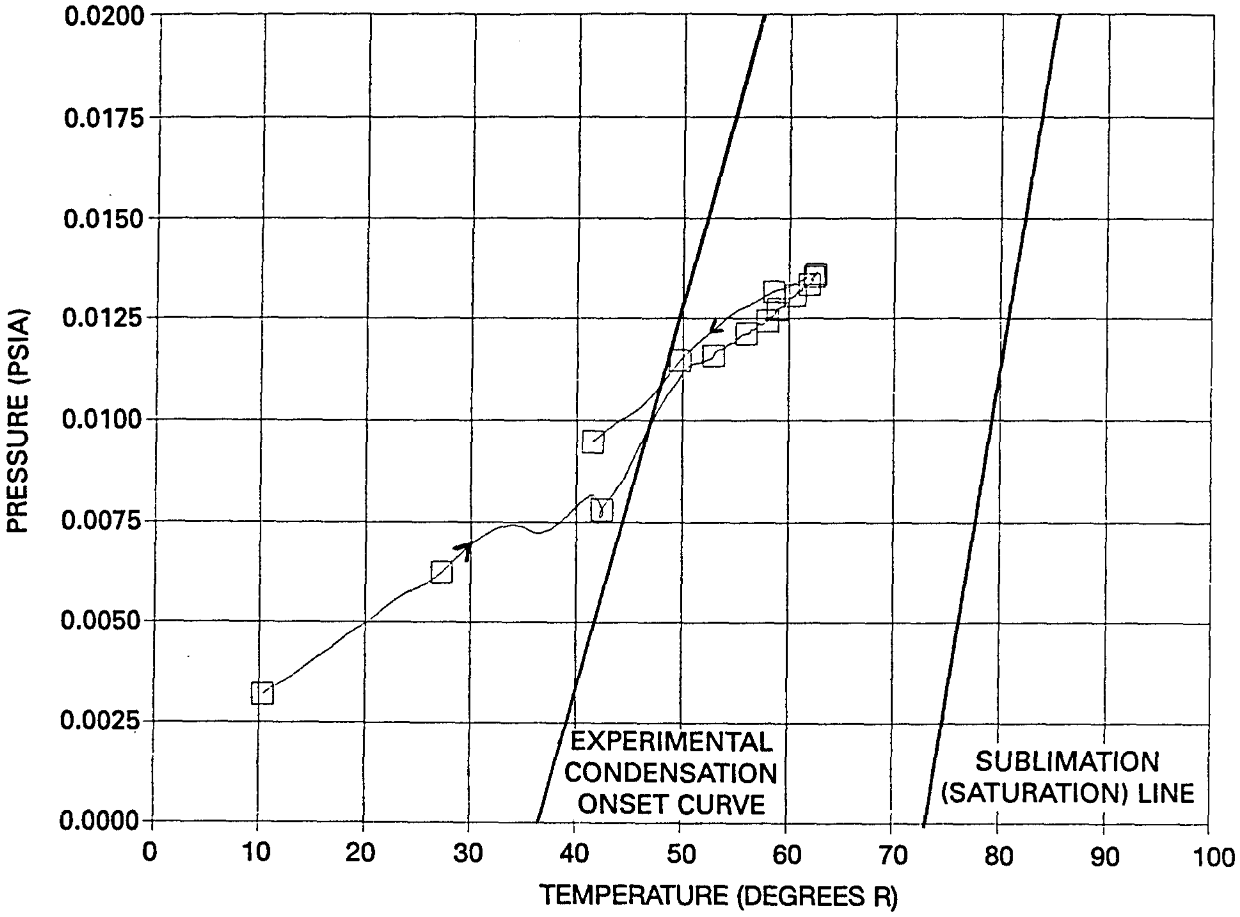

FIGURE A-9. TEST CELL PRESSURE VS. TEMPERATURE PLOT FOR MACH 18

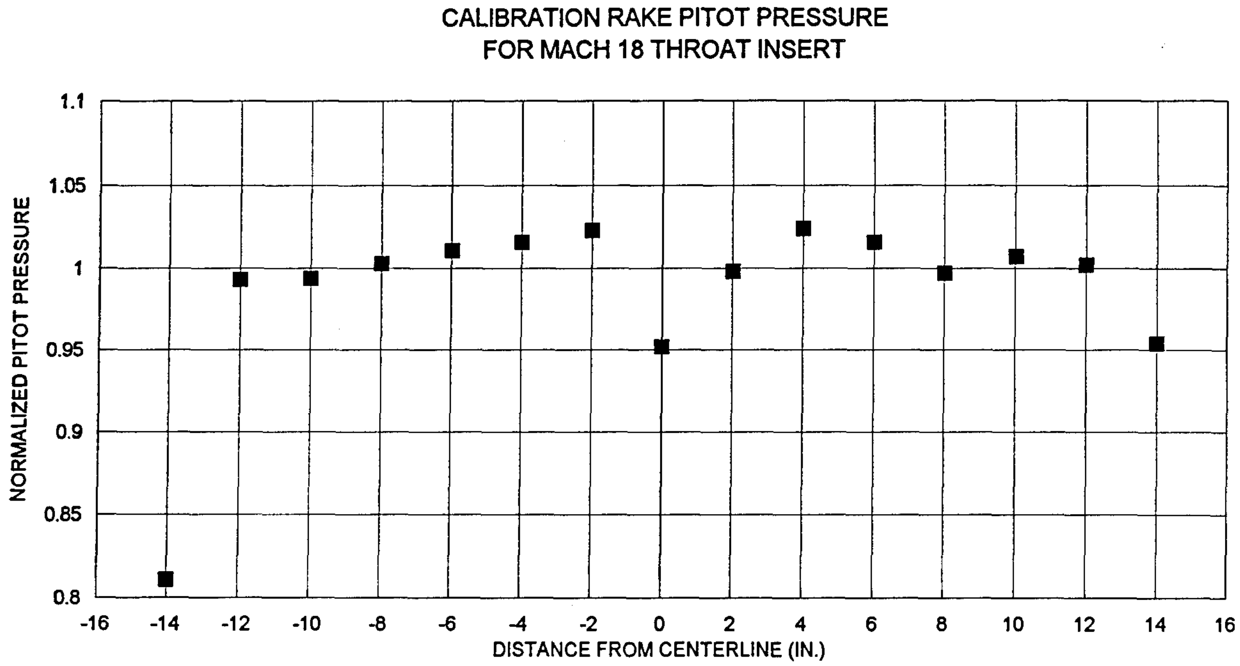

FIGURE A-10. NORMALIZED PITOT PRESSURE VS. DISTANCE FROM CENTERLINE FOR RUN 2375

TABLE A-1. TUNNEL 9 FLOW UNIFORMITY CALIBRATION FOR RUN 2347

WTR 1604, RUN 2347, STATION 24 inches

MACH = 17.39 P0 = 22320. psia T0 = 2646. degF PTAVG = 5.38 psia

NOMINAL FREESTREAM CONDITIONS

MACH	QINF psia	TINF degR	PINF psia	REINF 1/ft	UINF ft/sec	RHOINF lbm/ft3	VIP ft**1/2
17.39	2.923	59.9	1.38E-02	2.56E+06	6710.	6.01E-04	1.09E-02

PROFILES NORMALIZED TO NOMINAL

Probe #	Dist. from center (in)	PT	M	Q	T	P	RE	U	RHO	VIP
1	-24.00	0.210	1.374	0.210	0.534	0.111	0.387	1.004	0.208	2.209
2	-22.00	0.318	1.263	0.318	0.631	0.199	0.497	1.003	0.316	1.791
3	-20.00	0.442	1.181	0.443	0.720	0.317	0.609	1.002	0.440	1.514
4	-18.00	0.569	1.122	0.569	0.797	0.452	0.709	1.002	0.567	1.332
5	-16.00	0.676	1.083	0.676	0.854	0.577	0.788	1.001	0.675	1.220
6	-14.00	0.746	1.062	0.746	0.889	0.662	0.837	1.001	0.745	1.161
7	-12.00	0.831	1.038	0.831	0.928	0.771	0.894	1.001	0.830	1.098
8	-10.00	0.979	1.004	0.979	0.992	0.971	0.987	1.000	0.979	1.011
9*	-8.00	1.003	0.999	1.003	1.001	1.004	1.002	1.000	1.003	0.999
10	-6.00	0.990	1.002	0.990	0.996	0.985	0.994	1.000	0.989	1.005
11	-4.00	0.994	1.001	0.994	0.998	0.992	0.997	1.000	0.994	1.003
12	-2.00	0.957	1.009	0.957	0.983	0.940	0.974	1.000	0.957	1.022
13	0.00	0.870	1.029	0.870	0.945	0.822	0.919	1.000	0.869	1.074
14	2.00	0.916	1.018	0.917	0.966	0.884	0.948	1.000	0.916	1.045
15	4.00	0.989	1.002	0.989	0.996	0.984	0.993	1.000	0.989	1.006
16	6.00	0.986	1.003	0.986	0.994	0.981	0.992	1.000	0.986	1.007
17*	8.00	0.997	1.001	0.997	0.999	0.996	0.998	1.000	0.997	1.001
18	10.00	0.995	1.001	0.995	0.998	0.992	0.997	1.000	0.994	1.003
19	12.00	0.925	1.016	0.925	0.969	0.896	0.954	1.000	0.925	1.040
20	14.00	0.764	1.056	0.764	0.898	0.685	0.849	1.001	0.763	1.147
21	16.00	0.706	1.074	0.706	0.869	0.613	0.809	1.001	0.705	1.194
22	18.00	0.605	1.108	0.605	0.817	0.493	0.737	1.002	0.604	1.291
23	20.00	0.481	1.161	0.481	0.745	0.357	0.641	1.002	0.479	1.450
24	22.00	0.357	1.233	0.357	0.661	0.235	0.534	1.003	0.355	1.687
25	24.00	0.237	1.340	0.237	0.561	0.132	0.416	1.004	0.235	2.078

* - Averaged to determine PTAVG and nominal conditions.

TABLE A-2. TUNNEL 9 FLOW UNIFORMITY CALIBRATION FOR RUN 2349

WTR 1604, RUN 2349, STATION 24 inches

MACH = 17.64 PO = 22770. psia TO = 2660. degF PTAVG = 5.14 psia

NOMINAL FREESTREAM CONDITIONS

MACH	QINF psia	TINF degR	PINF psia	REINF 1/ft	UINF ft/sec	RHOINF lbm/ft3	VIP ft**1/2
17.64	2.790	58.6	1.28E-02	2.48E+06	6732.	5.70E-04	1.12E-02

PROFILES NORMALIZED TO NOMINAL

Probe #	Dist. from center (in)	PT	M	Q	T	P	RE	U	RHO	VIP
1	-24.00	0.201	1.386	0.201	0.525	0.105	0.376	1.004	0.199	2.258
2	-22.00	0.307	1.272	0.307	0.622	0.190	0.487	1.003	0.305	1.821
3	-20.00	0.433	1.186	0.433	0.714	0.308	0.601	1.002	0.431	1.531
4	-18.00	0.561	1.125	0.562	0.793	0.444	0.704	1.002	0.560	1.341
5	-16.00	0.671	1.085	0.671	0.852	0.570	0.784	1.001	0.669	1.225
6	-14.00	0.740	1.064	0.740	0.886	0.654	0.832	1.001	0.738	1.166
7	-12.00	0.779	1.052	0.779	0.904	0.703	0.859	1.001	0.778	1.136
8	-10.00	0.992	1.002	0.992	0.997	0.989	0.995	1.000	0.992	1.004
9*	-8.00	0.999	1.000	0.999	1.000	0.999	0.999	1.000	0.999	1.000
10	-6.00	1.061	0.988	1.061	1.024	1.086	1.036	1.000	1.061	0.971
11	-4.00	1.065	0.987	1.065	1.026	1.093	1.039	1.000	1.066	0.968
12	-2.00	0.979	1.004	0.979	0.991	0.970	0.987	1.000	0.979	1.011
13	0.00	0.892	1.024	0.892	0.955	0.852	0.933	1.000	0.892	1.060
14	2.00	0.933	1.014	0.933	0.973	0.908	0.959	1.000	0.933	1.036
15	4.00	1.055	0.989	1.054	1.022	1.078	1.033	1.000	1.055	0.973
16	6.00	1.061	0.988	1.061	1.024	1.087	1.037	1.000	1.062	0.970
17*	8.00	1.001	1.000	1.001	1.000	1.001	1.001	1.000	1.001	1.000
18	10.00	0.998	1.000	0.998	0.999	0.997	0.999	1.000	0.998	1.001
19	12.00	0.797	1.047	0.797	0.913	0.726	0.871	1.001	0.796	1.122
20	14.00	0.758	1.058	0.758	0.895	0.677	0.845	1.001	0.757	1.151
21	16.00	0.705	1.074	0.706	0.869	0.612	0.809	1.001	0.704	1.194
22	18.00	0.605	1.108	0.606	0.817	0.493	0.737	1.001	0.604	1.291
23	20.00	0.478	1.162	0.478	0.743	0.354	0.638	1.002	0.476	1.455
24	22.00	0.350	1.238	0.351	0.656	0.229	0.528	1.003	0.349	1.704
25	24.00	0.231	1.347	0.231	0.555	0.127	0.410	1.004	0.230	2.104

* - Averaged to determine PTAVG and nominal conditions.

TABLE A-3. TUNNEL 9 FLOW UNIFORMITY CALIBRATION FOR RUN 2370

WTR 1604, RUN 2370, STATION 24 inches

MACH = 17.98 PO = 21685. psia TO = 2757. degF PTAVG = 4.31 psia

NOMINAL FREESTREAM CONDITIONS

MACH	QINF psia	TINF degR	PINF psia	REINF 1/ft	UINF ft/sec	RHOINF lbm/ft3	VIP ft**1/2
17.98	2.339	58.0	1.03E-02	2.07E+06	6830.	4.64E-04	1.25E-02

PROFILES NORMALIZED TO NOMINAL

Probe #	Dist. from center (in)	PT	M	Q	T	P	RE	U	RHO	VIP
1	-24.00	0.259	1.316	0.259	0.581	0.150	0.440	1.003	0.258	1.984
2	-22.00	0.385	1.215	0.385	0.681	0.261	0.559	1.002	0.383	1.624
3	-20.00	0.522	1.142	0.522	0.770	0.401	0.673	1.002	0.520	1.391
4	-18.00	0.650	1.092	0.651	0.841	0.546	0.770	1.001	0.649	1.244
5	-16.00	0.783	1.051	0.783	0.906	0.709	0.862	1.001	0.782	1.132
6	-14.00	0.934	1.014	0.934	0.973	0.909	0.960	1.000	0.934	1.035
7	-12.00	0.951	1.010	0.951	0.980	0.932	0.970	1.000	0.951	1.026
8	-10.00	0.976	1.005	0.976	0.990	0.966	0.985	1.000	0.975	1.013
9*	-8.00	1.008	0.998	1.008	1.003	1.012	1.005	1.000	1.008	0.996
10	-6.00	1.002	1.000	1.002	1.001	1.003	1.001	1.000	1.002	0.999
11	-4.00	0.984	1.003	0.984	0.993	0.977	0.990	1.000	0.984	1.008
12	-2.00	1.001	1.000	1.001	1.001	1.002	1.001	1.000	1.001	0.999
13	0.00	0.980	1.004	0.980	0.992	0.972	0.988	1.000	0.980	1.010
14	2.00	0.981	1.004	0.981	0.992	0.973	0.988	1.000	0.981	1.010
15	4.00	0.979	1.004	0.979	0.991	0.970	0.987	1.000	0.979	1.011
16	6.00	0.986	1.003	0.986	0.995	0.981	0.992	1.000	0.986	1.007
17*	8.00	0.992	1.002	0.992	0.997	0.988	0.995	1.000	0.992	1.004
18	10.00	0.994	1.001	0.994	0.998	0.992	0.997	1.000	0.994	1.003
19	12.00	0.946	1.011	0.946	0.978	0.924	0.966	1.000	0.945	1.029
20	14.00	0.930	1.015	0.930	0.971	0.903	0.957	1.000	0.929	1.038
21	16.00	0.820	1.041	0.820	0.923	0.756	0.886	1.001	0.819	1.106
22	18.00	0.682	1.081	0.682	0.857	0.583	0.792	1.001	0.680	1.215
23	20.00	0.562	1.125	0.562	0.793	0.445	0.704	1.002	0.561	1.340
24	22.00	0.430	1.187	0.430	0.712	0.305	0.598	1.002	0.428	1.535
25	24.00	0.291	1.286	0.291	0.609	0.176	0.471	1.003	0.289	1.872

* - Averaged to determine PTAVG and nominal conditions.

TABLE A-4. TUNNEL 9 FLOW UNIFORMITY CALIBRATION FOR RUN 2375

WTR 1604, RUN 2375, STATION 24 inches

MACH = 17.24 P0 = 21090. psia T0 = 2615. degF PTAVG = 5.26 psia

NOMINAL FREESTREAM CONDITIONS

MACH	QINF psia	TINF degR	PINF psia	REINF 1/ft	UINF ft/sec	RHOINF lbm/ft3	VIP ft**1/2
17.24	2.856	60.0	1.37E-02	2.51E+06	6660.	5.96E-04	1.09E-02

PROFILES NORMALIZED TO NOMINAL

Probe #	Dist. from center (in)	PT	M	Q	T	P	RE	U	RHO	VIP
1	24.00	0.257	1.319	0.257	0.579	0.148	0.437	1.004	0.255	1.995
2	22.00	0.378	1.219	0.378	0.676	0.254	0.553	1.003	0.376	1.639
3	20.00	0.519	1.143	0.519	0.768	0.398	0.671	1.002	0.517	1.395
4	18.00	0.662	1.088	0.662	0.847	0.560	0.778	1.001	0.661	1.233
5	16.00	0.771	1.055	0.771	0.901	0.693	0.854	1.001	0.770	1.141
6	14.00	0.954	1.010	0.954	0.981	0.936	0.972	1.000	0.954	1.024
7	12.00	1.002	1.000	1.002	1.001	1.002	1.001	1.000	1.002	0.999
8	10.00	1.007	0.999	1.007	1.003	1.010	1.004	1.000	1.007	0.997
9*	8.00	0.997	1.001	0.997	0.999	0.996	0.998	1.000	0.997	1.002
10	6.00	1.016	0.997	1.016	1.006	1.023	1.010	1.000	1.016	0.992
11	4.00	1.024	0.995	1.024	1.010	1.034	1.015	1.000	1.024	0.988
12	2.00	0.998	1.000	0.998	0.999	0.997	0.999	1.000	0.998	1.001
13	0.00	0.952	1.010	0.952	0.980	0.933	0.971	1.000	0.952	1.025
14	-2.00	1.023	0.995	1.023	1.009	1.032	1.014	1.000	1.023	0.989
15	-4.00	1.016	0.997	1.016	1.007	1.023	1.010	1.000	1.016	0.992
16	-6.00	1.011	0.998	1.011	1.004	1.015	1.006	1.000	1.011	0.995
17*	-8.00	1.003	0.999	1.003	1.001	1.004	1.002	1.000	1.003	0.998
18	-10.00	0.994	1.001	0.994	0.998	0.992	0.997	1.000	0.994	1.003
19	-12.00	0.993	1.001	0.993	0.997	0.990	0.996	1.000	0.993	1.004
20	-14.00	0.811	1.044	0.811	0.919	0.744	0.880	1.001	0.810	1.113
21	-16.00	0.731	1.066	0.731	0.881	0.643	0.826	1.001	0.729	1.173
22	-18.00	0.613	1.105	0.613	0.821	0.502	0.743	1.002	0.612	1.282
23	-20.00	0.480	1.161	0.480	0.744	0.356	0.640	1.002	0.478	1.452
24	-22.00	0.345	1.242	0.345	0.652	0.224	0.523	1.003	0.343	1.717
25	-24.00	0.222	1.359	0.222	0.546	0.120	0.400	1.004	0.220	2.150

* - Averaged to determine PTAVG and nominal conditions.

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13. ABSTRACT *(Maximum 200 words)*

This report describes the results of the High Mach Number Development Program performed at the White Oak, Maryland site of the Dahlgren Division, Naval Surface Warfare Center. The goal of this program was to expand the capabilities of the Hypervelocity Wind Tunnel Number 9 (Tunnel 9) to include operation at Mach 18. The constraints of this program involved using the existing Mach 14 setup with as little modification as necessary.

There were two major areas of interest for this program, the heater and the nozzle. The required supply temperature for Mach 18 operation is above the current capabilities of the Tunnel 9 Mach 14 heater. Utilizing supercooled flow conditions lowered the required supply temperature to within the Mach 14 heater capability. The current Mach 14 nozzle was used and the throat section was replaced with a new hardware set designed to achieve the correct nozzle throat-to-exit area ratio to obtain the higher Mach number.

Forty-one runs were carried out in Tunnel 9 in support of this program. The Mach number capability in Tunnel 9 has been extended to Mach 16.5. For this condition the flow has a 30-inch test core with Pitot pressure deviations of -1.1% to +1.3% and 3.5 seconds of good run time. A Mach 18 capability has also been investigated. Research efforts to achieve acceptable Mach 18 conditions are continuing.

14. SUBJECT TERMS

Heater	Nozzle	Throat-to-Exit Area Ratio
Hypersonic	High Mach Number	

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