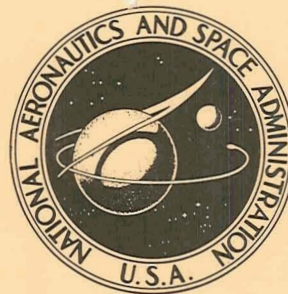


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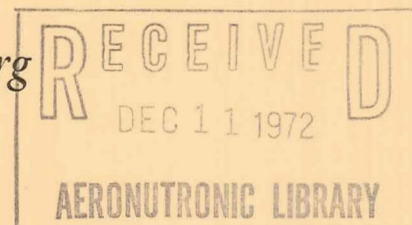
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CALIBRATION OF  
LEWIS HYPERSONIC TUNNEL FACILITY  
AT MACH 5, 6, AND 7

*by Richard R. Cullom and Erwin A. Lezberg*

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# CALIBRATION OF LEWIS HYPERSONIC TUNNEL FACILITY AT MACH 5, 6, AND 7

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## SUMMARY

Results of the initial calibration tests and a description of this true simulation facility are presented. Facility nozzles were calibrated over a range of stagnation pressure and temperature from 140 to 700 newtons per square centimeter and 1100 to 1750 K. The Reynolds number varied from  $1.77 \times 10^6$  to  $7.44 \times 10^6$  per meter. Mach numbers in the inviscid core of the three nozzles were  $5.17 \pm 0.03$ ,  $6.05 \pm 0.02$ , and  $7.25 \pm 0.08$ . Useable core diameter at the nozzle exit plane varied from 69 to 86 centimeters. True simulation with these performance capabilities and the test section size presently make this a unique operating facility. There was no measurable axial gradient in Mach number or total temperature over the portion of the enclosed free-jet test section surveyed. Over the range investigated there was no apparent Reynolds number effect on the test section Mach number.

## INTRODUCTION

The development of air-breathing engines suitable for propulsion of hypersonic vehicles will require ground test facilities capable of true aerothermodynamic simulation of the flight environment. Indeed, the lack of such facilities of adequate size has severely restricted the advance of propulsion system technology for hypersonic aircraft. Recognizing this, modifications to an existing heat-transfer facility were made to provide the capability for testing of scaled hypersonic air-breathing propulsion engines and components.

The Hypersonic Tunnel Facility (HTF) at the Plum Brook Station of the Lewis Research Center was designed for testing propulsion systems and components with synthetic air at Mach numbers of 5, 6, and 7 over a simulated altitude range of 20.7 to 39.6 kilometers. The free-jet nozzles were approximately 107 centimeters in exit diameter. This true simulation facility will be further described in this report along with the results of flow calibration tests.

## FACILITY DESCRIPTION

The HTF is a blowdown enclosed free-jet tunnel designed for propulsion testing with true temperature, composition, and altitude simulation over the Mach number range of 5 to 7. A schematic of the facility is shown in figure 1. The facility uses an induction-heated, drilled-core graphite storage heater to heat nitrogen to a nominal temperature of 2500 K at a maximum design pressure of 828 newtons per square centimeter. The nitrogen is mixed with ambient-temperature oxygen to produce synthetic air. Diluent nitrogen is added with the oxygen in the mixer at tunnel operating Mach numbers below 7 to supply the correct weight flow to the 107-centimeter-exit-diameter free-jet nozzles. Altitude simulation is provided by a diffuser and single stage steam ejector. Three interchangeable axisymmetric contoured nozzles provide nominal test Mach numbers of 5, 6, and 7. Maximum run times are estimated to be 2 to 3 minutes, depending on Mach number and altitude.

### Heat Exchanger

The graphite storage heater is shown in figure 2. The heater core consists of a stacked array of 15 drilled graphite cylinders, 1.83 meters in diameter and 9.15 meters high. The graphite sections are separated by short plenum sections and aligned with internal hexagonal key blocks. Typical sections and key blocks before assembly are shown in figure 3. Preliminary design considerations for the heater core and results of pilot scale tests are discussed in reference 1. The final design of the core made use of a transient heat-conduction program (ref. 2). Hole sizes in the graphite sections were graded, from the bottom to the midsection of the heater at 2.86, 2.54, and 1.91 centimeter in order to maximize safety factors for thermal stress because of the axial temperature gradient. Holes were arranged with equilateral triangular spacing of 3.8 centimeters. The graphite core assembly was thermally insulated with a 17.8-centimeter-thick layer of carbon felt and a 5.1 centimeter thick glazed silicon carbide tile shell. Water-cooled copper induction coils were located at the outside diameter of the tile shell and were separated axially into four heating sections. Power to the coils is a maximum of 3 megawatts from a 180-hertz, single-phase, 750-volt supply. The heater assembly was contained within a steel pressure vessel with a 10.2-centimeter-thick wall, 2.8 meter in diameter, and 12.2 meters high. The heater was designed to supply a maximum nitrogen weight flow of 63.5 kilograms per second at a nominal temperature of 2500 K. The gaseous nitrogen is supplied from a railroad tank car of 20 550-cubic-meter capacity at 3450 newtons per square centimeter pressure.

## Mixing Section

From the heater, hot nitrogen flows through graphite-lined and carbon-felt insulated water-cooled piping to the isolation valve, water-cooled mixer, and nozzle (fig. 4). The valve is a two-position shutter, which was designed to isolate the heater from atmospheric oxygen during periods of heating the graphite core at low pressure. Upstream of the mixer section, nitrogen and oxygen at ambient temperatures are premixed and injected into the heated nitrogen stream through an injection flange. Injection flanges are provided for each of the facility nozzles, which have differing diluent weight-flow requirements. The diluent gas mixture is injected radially from slot shaped holes located at 15 equally spaced circumferential positions and arranged in 2, 3, or 4 rows. Hole sizes and row spacing were optimized for design mixture ratios during a simulation study conducted at one-third scale. Jet penetration was based on mass flux ratios. The mixer consists of an Inconel 718 cylindrical liner, 1.5 meter long and 0.46 meter in diameter, water cooled and separated from the external pressure shell by O-ring seals. During the calibration tests described herein, a film injection flange was provided downstream of the diluent injection to cool the mixer liner inlet section and O-ring seals. Up to 4.5 kilograms per second of nitrogen were injected through small axially directed holes from a rearward facing step. This film-cooling device proved to be relatively inefficient and is being replaced with a water-cooled section. The diluent and film-cooling nitrogen gas is supplied from the same source as the heater gas. The oxygen is supplied by a tank farm of 11 800-cubic-meter capacity at 1660 newtons per square centimeter pressure.

## Facility Nozzles

The supersonic axisymmetric nozzles were designed by the real-gas method of characteristics using a Sauer starting line (ref. 3). Frozen composition was assumed in the calculations since, for the temperature range of interest, there were insignificant differences in area ratio between equilibrium and frozen flow. The inviscid nozzle contour was then adjusted by adding the boundary layer displacement thickness calculated by the method of Sasman and Cresci (ref. 4). The subsonic and supersonic sections of the nozzles up to the Sauer line intersection were formed from hyperbolic arcs. Final contours of the Mach 5 and 7 nozzles were faired with a spline fit procedure. All nozzles were made the same axial length by choice of maximum expansion angle and cutoff length beyond the intersection of the boundary layer and last Mach line. Three interchangeable nozzles which provided nominal test Mach numbers of 5, 6, and 7 were fabricated using an electroforming process. The Mach 5 nozzle was completely electroformed from nickel. The Mach 6 and 7 nozzle throat sections were machined from zirconium copper



forgings and electroformed to nickel expansion sections. The design conditions and physical dimensions of the water-cooled nozzles along with the calculated displacement thicknesses at the nozzle exit are shown in table I. The facility operating range with each of the Mach 5, 6, or 7 nozzles installed is shown in figure 5.

## Test Chamber

The calibration rake mounted in the free-jet section enclosed within the 7.6-meter-diameter test chamber is shown in figure 6. The facility nozzle and the diffuser exhaust duct penetrate the chamber wall through inflatable seals. The test section free-jet length can be varied to a maximum of 3.0 meters, depending upon the axial position of the adjustable diffuser-collector section. A cylindrical, water-cooled shroud was installed, cantilevered from the collector cone for a Mach 6 and Mach 7 calibration test. In addition, for these tests, an annular boundary-layer injection nozzle (fig. 6), was mounted on the facility nozzle at its exit plane. The shroud and the boundary-layer injector nozzle were installed to facilitate tunnel starting for large blockage models. An overhead hydraulically operated model injection system is available to swing test models into the flow and translate the model axially a maximum of 76 centimeters. The model suspension system is also capable of providing a maximum angle of attack of  $5^{\circ}$ .

## Exhaust System

The exhaust system (fig. 7) consists of a supersonic diffuser, combined subsonic diffuser and spray cooler and single-stage steam ejector. The supersonic diffuser consists of the translatable water-cooled inlet section, which was used to vary the free-jet length terminating in a 1.4-meter-diameter collection cone, and a heat-sink design constant diameter section, 9.2 meters long and 1.1 meter diameter. The subsonic diffuser and spray cooler is a conical section, 11.8 meters long by 2.9 meters in diameter at the entrance to the steam ejector and is provided with in-stream water spray nozzles designed to cool the exhaust gases to saturation temperature. The steam ejector uses a coaxial steam nozzle flowing 265 kilograms per second of steam at 100 newtons per square centimeter pressure. Performance of the ejector is shown in figure 8, which includes the results of facility checkout runs and scale model tests performed by the manufacturer.

## Data System

The main data recording system is an analog to digital converter capable of recording 200 channels of data on magnetic tape at a rate of 1875 samples per second. For the calibration test series each data channel was sampled 17 times per second. Secondary data recording capacity was provided by multichannel oscillograph and strip-chart recorders. In addition, pitot pressure and total temperature distributions in the free jet were displayed on oscilloscopes providing real time visual observation of tunnel operation and performance during a run. Instant replay of the displayed data was available for postrun analysis.

## OPERATING PROCEDURE

The induction heater coils were energized approximately 60 hours prior to a test run series. After the graphite core sections were heated to the approximate operating temperature the electrical power input was set to maintain this temperature level. The heater remained at an elevated temperature during the test series. The isolation valve was opened and steam flow to the ejector was initiated to lower the pressure in the test chamber immediately before the test gas flow was started. The ejector was maintained in operation until after the end of the test run. The test run was initiated by opening the heater inlet valve, which was preprogrammed to maintain a specified pressure-time relation and allowed the inflowing nitrogen to pressurize the heater annulus and core. After heater pressurization had begun, unheated diluent nitrogen and oxygen were introduced into the mixer injection flange. The oxygen to nitrogen ratio of the test gas was regulated by servo-controllers that varied the oxygen and diluent nitrogen weight flows proportionally to the measured nozzle inlet pressure. Ratios were set on the controllers assuming that the nozzle inlet gas temperature was known. Depending on the length of steady-state run time required, it was possible to obtain a second steady-state run at a higher stagnation pressure during a single test run. At the end of the steady-state run, the heater inlet valve was closed, and the heater depressurization valve opened allowing the heater volume to depressurize. This was followed by closing the oxygen supply valve and after a delay the diluent nitrogen valve. The steam valve to the ejector was closed to allow the test chamber to return to atmospheric pressure and finally, the heater isolation valve was closed.

## CALIBRATION

To calibrate the facility over a wide range of operating conditions with minimal

setup and test time, nitrogen was used instead of the normal synthetic air mixture (table II). This procedure was deemed valid since the characteristics of nitrogen and air are similar and no differences in calibration data would be expected. The Mach 6 nozzle was calibrated using both test gases to verify this assumption. During engine testing synthetic air is required.

## Instrumentation and Procedure

The water-cooled survey rake used to calibrate the test section flow stream is shown in figure 9. The rake spanned 91.5 centimeters and included 19 pitot pressure and nine temperature probes, which are described and located in the figure. The calibration rake could be mounted in either the vertical or horizontal position to verify flow symmetry. For all calibration tests the minimum Reynolds number based on pressure probe hole diameter was 33 000. The pitot probes were connected to strain-gage transducers. The temperature probes had removable inserts so that thermocouple wire type could be matched to the test-gas temperature regime. For the Mach 5 tests and the Mach 6 air tests, platinum/platinum - 13-percent-rhodium thermocouple inserts were used. For the Mach 7 calibration and the Mach 6 nitrogen runs the test section gas temperature distribution was measured with iridium/iridium - 40-percent-rhodium thermocouples installed in the survey rake probes.

The upstream stagnation conditions were measured in a heat-sink nozzle inlet section. Stagnation pressure was obtained at two static-pressure taps at the wall of the nozzle inlet section, stagnation temperature from two water-cooled aspirated thermocouple probes (fig. 10). For the Mach 5 and 6 calibrations the probes were assembled with platinum/platinum - 13-percent-rhodium thermocouples. For the Mach 7 calibration the thermocouple assembly was replaced with an iridium/iridium - 40-percent-rhodium assembly.

At the beginning of a test run the calibration rake was located in the free jet at the upstream limit of its axial travel. The stagnation pressure was increased to start the tunnel and establish hypersonic flow conditions at the test section. When steady-state data were obtained at the upstream position, the rake was traversed downstream to detect any axial gradients in the pitot pressure or stream total temperature. The survey rake was stopped at one or two other axial positions depending on the free-jet length. Data were recorded continually throughout the test run. This procedure was followed with the rake in the vertical plane for the calibration of the Mach 5 nozzle. These runs were then repeated with the rake positioned in the horizontal plane. The survey rake was maintained in the horizontal position for the Mach 6 and 7 calibrations after circumferential uniformity was observed from the Mach 5 tests.



## Mach Number Calculation

The test section Mach numbers were calculated from the ratios of the survey rake pitot pressure to stagnation pressure including real gas effects. The test-gas temperatures used in the real-gas correction were obtained from the calibration rake thermocouple readings, which were corrected for recovery and radiation losses.

Mach number profiles calculated by this method were then examined to determine which data points were in the boundary layer. These Mach numbers were then recalculated by using the static pressure as obtained from the mean inviscid Mach number. A real gas calculation was used to obtain the corrected value of Mach number from the ratio of the pitot to static pressure. Calculated Mach numbers downstream of the shock wave from the nozzle lip are presented uncorrected. The shock results from a mismatch of nozzle exit and test chamber pressure. Although the mismatch was small, it represents the boundary of the inviscid stream.

## RESULTS

### Test Conditions

Calibration tests of the hypersonic tunnel facility were conducted at the conditions shown in table II. Nominal test section Mach numbers of the facility nozzles were 5, 6, and 7. The Mach 5 nozzle was installed with a free-jet length to nozzle exit diameter ratio  $L/D_e$  of 2.28. The survey rake was installed at the nozzle exit in the vertical and horizontal planes for alternate test runs. The Mach 6 nozzle was calibrated at three free-jet lengths,  $L/D_e = 2.26, 1.55, \text{ and } 0.61$ . The shortest jet length resulted from installing a cylindrical shroud (cantilevered from the collector). This shrouded configuration in conjunction with an annular boundary-layer injector nozzle was tested to ascertain its effect on tunnel starting. See reference 5 for model tests of this configuration. The survey rake was maintained in the horizontal plane for the Mach 6 and Mach 7 tests. The Mach 7 nozzle was surveyed at free-jet lengths of  $L/D_e = 1.52 \text{ and } 0.60$ . Calibrations of the three nozzles were made with nitrogen as the test gas over the altitude range required for a planned test program and were not necessarily at the facility operating limits. The Mach 6 nozzle was also calibrated with a nitrogen-oxygen mixture with the composition of air at a total temperature close to the correct value for true flight simulation. No differences in calibration data due to the change from nitrogen to synthetic air were expected. The Reynolds number for these calibration tests varied from  $1.77 \times 10^6$  to  $7.44 \times 10^6$  per meter.

## Mach Number Surveys

Mach 5 nozzle. - Radial Mach number profiles obtained at three axial stations in the vertical (fig. 11) and horizontal planes (fig. 12) are shown for two stagnation pressures. The data points that were determined to be in the boundary-layer flow were corrected and are indicated by the tailed symbols. The mean free-stream Mach number was 5.17. The Mach number profiles were flat within  $\pm 0.03$  except for disturbances near the test section centerline at the two upstream axial stations. The profiles at the upstream survey station showed a weak expansion wave intersecting the centerline. A compression wave appeared at the centerline of the profile at the middle axial station. The strength of these waves was comparable in the two survey planes. Also, a disturbance was noted in the vertical plane profiles at the downstream survey station at the bottom of the vertically positioned rake (left side of the figure). This shock wave emanated from boundary-layer calibration probes in the flow near the bottom center of the nozzle exit plane. Note that the disturbance attributed to the boundary layer rake was absent in the horizontal plane profiles (fig. 12). Comparison of the vertical and horizontal Mach number surveys indicate that the flow in the test section was symmetrical about the centerline. At the upstream survey station the Mach number profiles showed a usable inviscid core diameter of 86 centimeters. At the intermediate axial station the core diameter was 76 centimeters, and at the downstream station in the horizontal plane the core diameter was 61 centimeters. Over the distance surveyed there was no measurable axial gradient in Mach number at either stagnation pressure. In addition, there was no measurable effect on the Mach number profiles over the range of Reynolds number investigated.

Mach 6 nozzle. - Mach number profiles calculated at the nozzle-exit plane for tests with simulated air are shown in figure 13. At the two pressure levels investigated, the profiles exhibit a mean core Mach number of  $6.05 \pm 0.02$ . Mach number profiles obtained with nitrogen at two stagnation pressures are shown in figure 14. The mean core Mach number at both pressures was  $6.14 \pm 0.02$ . The difference in mean core Mach number was attributed to the difference in test-gas total temperature level and not gas composition. This temperature effect will be discussed later. For a given test gas the mean Mach numbers are equal at both stagnation pressures. Therefore, there was no significant Reynolds number effect on Mach number over the range investigated. Also the Mach number gradient over the axial distance surveyed in the nitrogen test (fig. 14) was negligible. The Mach profiles were flat, and no significant wave disturbances appeared in the inviscid core. The usable core diameter at the nozzle exit was 71 centimeters at either pressure level for both the nitrogen and simulated air tests. At the furthest downstream survey station the core diameter was 61 centimeters for the nitrogen test.

Varying the free-jet length ratio from  $L/D_e = 1.55$  to 2.26 does not significantly

change the shape or level of the Mach number profile. In figure 14(a) the two upstream axial position Mach profiles were recorded with a free jet length ratio of 1.55. The downstream station profile was obtained with a free jet length ratio of 2.26. Even though these data were obtained from separate test runs, the inviscid core portion of the three profiles fell within a  $\pm 0.5$ -percent band. Corresponding agreement was observed when the data (fig. 14(b)), obtained at a jet length ratio of 2.26, were compared with other data obtained at a length ratio of 1.55.

Composition of the test gas was adjusted to simulate air with an oxygen to total gas flow weight ratio of 23.3 percent. Measurement of experimental gas weight flows for the high-pressure run resulted in a weight ratio of 22.4 percent. Results of limited gas sampling tests are shown in table III. Gas samples were withdrawn through the aspirating stagnation thermocouple probes (fig. 10) and collected in high-pressure stainless-steel bottles. The samples were later analyzed with a mass spectrometer. Comparison of the gas samples obtained at the higher stagnation pressure with the metered oxygen to total flow ratio showed samples that are slightly oxygen rich. Since the samples were extracted from probes located at one-third the distance from the wall to the centerline, they may reflect incomplete mixing of the film-cooling nitrogen, which was introduced at the inlet to the mixer, or incomplete mixing of the cold oxygen-nitrogen mixture with the hot nitrogen stream. Comparison of the metered oxygen to total flow ratio with the desired composition of air showed the metered ratio to be low in oxygen. Since the automatic control system presently does not compensate for the actual mixture temperature at the nozzle inlet, a 2-percent-low error in oxygen weight percent would be expected because of the lower than programmed mixture total temperature. The trace amounts of hydrogen originate from hydrocarbon impurities in the graphite or water in the nitrogen gas and the carbon dioxide results from oxidation of carbon dust or hydrocarbon impurities. Argon was an impurity in the nitrogen gas supply.

Mach 7 nozzle. - The Mach number profiles recorded in the horizontal plane at two axial stations are shown in figure 15(a). The mean core Mach number was  $7.25 \pm 0.08$ , and the usable inviscid core diameter was approximately 69 centimeters. At the lower stagnation pressure (fig. 15(b)) the mean Mach number was  $7.30 \pm 0.11$ , and the inviscid core diameter was 66 centimeters. Expansion waves were indicated in the free jet by the shape of the Mach number profiles. The variation in Mach number from the design value can partially be attributed to the gas temperature being below the design value. This effect will be discussed later.

The calibration tests of the Mach 7 nozzle were conducted at an open jet length ratio of 1.52. An attempted calibration run at a jet length ratio of 2.2 was unproductive because of unstable flow conditions. Apparently at the longer free-jet length, flow spilled into the chamber around the diffuser collector cone and could not be effectively pumped by the jet to maintain a ratio of test chamber to free-stream static-pressure low enough to enable the diffuser to remain started.

## Total Temperature Surveys

Mach 5 nozzle. - Radial temperature profiles, which have been corrected for recovery and radiation losses are shown in figure 16(a) for the vertical plane and in figure 16(b) for the horizontal plane. The data were recorded at three axial stations. The temperature profiles appear to be relatively flat and show a mean value of approximately 1110 K. This mean gas temperature was 110 K below the nozzle design temperature. All temperature data were within a  $\pm 2$ -percent band over the axial distance surveyed in the test section.

The corrected temperature profiles obtained at a lower pressure in the vertical and horizontal plane are shown in figures 17(a) and (b), respectively. The shape of the temperature profiles can probably be attributed to cold nitrogen injected from the wall in the mixer section not penetrating sufficiently into the stream of hot nitrogen flowing from the heater. Diluent nitrogen flow rates during these tests were considerably below design and pressure drop through the diluent injection holes appeared to be insufficient to insure adequate penetration into the hot nitrogen stream.

Mach 6 nozzle. - Temperature distributions at the nozzle exit for simulated air are shown in figure 18. The mean core gas temperature was approximately 1580 K, or 70 K below the nozzle design temperature. The profile at the higher pressure was flat with all the data falling within a  $\pm 2$ -percent band. The profile at the lower pressure was not as flat, perhaps exhibiting a decreased penetration by the cold oxygen-nitrogen mixture injected at the wall.

Temperature profiles at three axial stations are shown in figure 19 for nitrogen gas at two stagnation pressures. The mean temperature level at the high pressure was approximately 1360 K, which is 290 K below the nozzle design temperature. At the lower pressure the mean gas temperature was approximately 1290 K. The temperature profiles were fairly flat at both pressures with the inviscid core data within a  $\pm 2$ -percent band. There appeared to be no appreciable thermal gradient in the axial direction in the region surveyed at either pressure level.

Mach 7 nozzle. - Temperature profiles at two stagnation pressures are shown in figure 20. At the higher pressure (fig. 20(a)) the mean core temperature was approximately 1750 K or 380 K below the nozzle design point. The mean core temperature at the lower stagnation pressure (fig. 20(b)) was 1530 K. The temperature distributions were somewhat rounded and indicated incomplete penetration by the wall-injected cold nitrogen.

## Effect of Gas Temperature on Mach Number Determination

Measured gas temperatures for the calibration runs were considerably below the

design values except for Mach 5 nozzle tests and the Mach 6 synthetic air tests. The Mach number profiles for the Mach 6 nozzle approached the design value as temperature was increased. Differences at Mach 5 are probably due to an overestimation of the boundary-layer displacement thickness resulting in a slight overexpansion. The results of the Mach 7 calibrations indicate expansion waves present in the test section. Since the temperatures in these tests were considerably below design (230 to 480 K) both the estimation of the displacement thickness and the change in thermodynamic properties of the gas may have contributed to the higher than design Mach number.

The boundary-layer displacement thicknesses used in the correction of the inviscid nozzle contour were calculated by the method of Sasman and Cresci (ref. 4). Boldman et al. (ref. 6) showed that the Sasman-Cresci theory overpredicted the experimentally determined displacement thicknesses by 25 percent in a Mach 4.4 nozzle with a wall- to stagnation-temperature ratio of 0.6. The facility nozzles calibrated herein operated at lower wall-temperature ratios than the nozzle tested in reference 6. For these cases of relatively high heat-transfer rates to the nozzle wall the gas density near the wall is relatively high. This factor could result in the actual displacement thickness being thinner than the values calculated from the Sasman-Cresci theory. The Sasman-Cresci theory does not include an energy consideration and therefore can overpredict the displacement thickness for highly nonadiabatic nozzle flows.

## Tunnel Starting

The starting characteristics of the facility nozzles with the calibration rake installed are shown in table IV. The calibration rake represents approximately 13 percent blockage. The starting pressure ratio was defined as the ratio of the upstream stagnation pressure at the time the shock wave passes the calibration rake to the test chamber pressure before supersonic flow was established in the test section. As expected, the starting pressure ratio increases as the Mach number increases. At a given Mach number the pressure ratio decreases as the free-jet length decreased. The annular boundary-layer injector nozzle, which was installed on the Mach 6 and 7 nozzles at the shortest jet length tested, contributed to the decrease in starting pressure ratio. An attempt to test the Mach 7 nozzle at a jet length ratio of 2.2 was unsuccessful because of a high test chamber to stream static-pressure ratio that did not allow the diffuser to remain started.



## SUMMARY OF RESULTS

The Lewis hypersonic tunnel facility was calibrated at Mach 5, 6, and 7. The facility nozzles were calibrated over a range of Reynolds number from  $1.77 \times 10^6$  to  $7.44 \times 10^6$  per meter and a ratio of test section free-jet length to nozzle exit diameter ratio of 0.60 to 2.28. The following results were obtained:

1. The Mach 5 nozzle displayed a fairly flat Mach profile with a mean free-stream Mach number of  $5.17 \pm 0.03$ . The flow in the test section was symmetrical about the centerline in both the vertical and horizontal planes surveyed. There was an 86-centimeter-diameter usable flow core at the nozzle exit.

2. The facility was operated at Mach 6 with a test gas composed of 22.4 percent oxygen by weight, successfully simulating air. The Mach number profile was flat at a mean free-stream value of  $6.05 \pm 0.02$ . There was a usable core flow diameter of 71 centimeters at the nozzle exit.

3. The Mach 7 nozzle displayed a mean Mach number of  $7.25 \pm 0.08$ . The usable inviscid core was 69 centimeters in diameter.

4. Within the measurable accuracy there was no axial gradient in Mach number or total temperature over the portion of the test section surveyed.

5. Over the range investigated there was no apparent Reynolds number effect on the test section Mach number.

6. Addition of a boundary-layer injector nozzle and a test section shroud improved the tunnel starting characteristics by lowering the tunnel starting pressure ratio.

Lewis Research Center,  
National Aeronautics and Space Administration,  
Cleveland, Ohio, July 28, 1972,  
762-75.

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TABLE I. - FACILITY NOZZLE CONDITIONS AND DIMENSIONS

Simulated conditions			Nozzle design stagnation conditions				Nozzle dimensions						
Mach number	Altitude		Total pressure		Total tem- perature		Throat diameter		Exit diameter		Nozzle length	Calculated exit displacement thickness	
	ft	km	psia	N/cm <sup>2</sup>	°R	K	in.	cm	in.	cm	in. cm	in.	cm
5	68 000	20.72	410	283	2200	1220	7.228	18.37	41.636	105.8	181 460	1.765	4.48
6	72 000	21.94	1200	828	2965	1650	4.860	12.35	42.052	106.8	181 460	1.311	3.33
7	93 000	28.65	1200	828	3830	2130	3.174	8.06	42.718	108.5	181 460	1.913	4.86

TABLE II. - HYPERSONIC TUNNEL FACILITY CALIBRATION CONDITIONS



Nozzle Mach number	Test gas	Stagnation pressure		Stagnation temperature		Reynolds number		Survey rake position
		psia	N/cm <sup>2</sup>	°R	K	per ft	per m	
5	Nitrogen 	206	142	1995	1110	1.16×10 <sup>6</sup>	3.80×10 <sup>6</sup>	Vertical
		411	283	2010	1120	2.27	7.44	Vertical
		207	143	2000	1110	1.17	3.84	Horizontal
		412	284	2000	1110	2.27	7.44	Horizontal
6	Nitrogen	472	326	2320	1290	1.01×10 <sup>6</sup>	3.31×10 <sup>6</sup>	Horizontal 
		930	642	2440	1360	1.94	6.36	
	Air	476	328	2820	1570	.96	3.15	
		931	642	2850	1580	1.86	6.10	
7	Nitrogen	500	345	2700	1500	0.54×10 <sup>6</sup>	1.77×10 <sup>6</sup>	Horizontal
		1017	702	3150	1750	.91	2.99	Horizontal

TABLE III. - ANALYSIS OF SYNTHETIC AIR SAMPLES AT MACH 6

Probe	Stagnation pressure, N/cm <sup>2</sup>	Mass fraction				
		N <sub>2</sub>	O <sub>2</sub>	A	CO <sub>2</sub>	H <sub>2</sub>
A	328	0.7730	0.2250	0.00069	0.00061	0.00003
A	642	.7580	.2410	.00069	.00046	.00006
B	642	.7546	.2435	.00069	.00107	.00008

TABLE IV. - HYPERSONIC TUNNEL FACILITY  
OPERATING CHARACTERISTICS

[13 Percent blockage.]

Facility nozzle	Free-jet length ratio, $L/D_e$	Start-unstart stagnation to test chamber pressure ratio	
		Start	Unstart
Mach 5	2.28	112	56
Mach 6	2.26	290	--
	1.55	276	155
Mach 7	<sup>a</sup> .61	177	111
	1.52	480	228
	<sup>a</sup> .60	---	166

<sup>a</sup>Operated with annular boundary-layer injector nozzle.

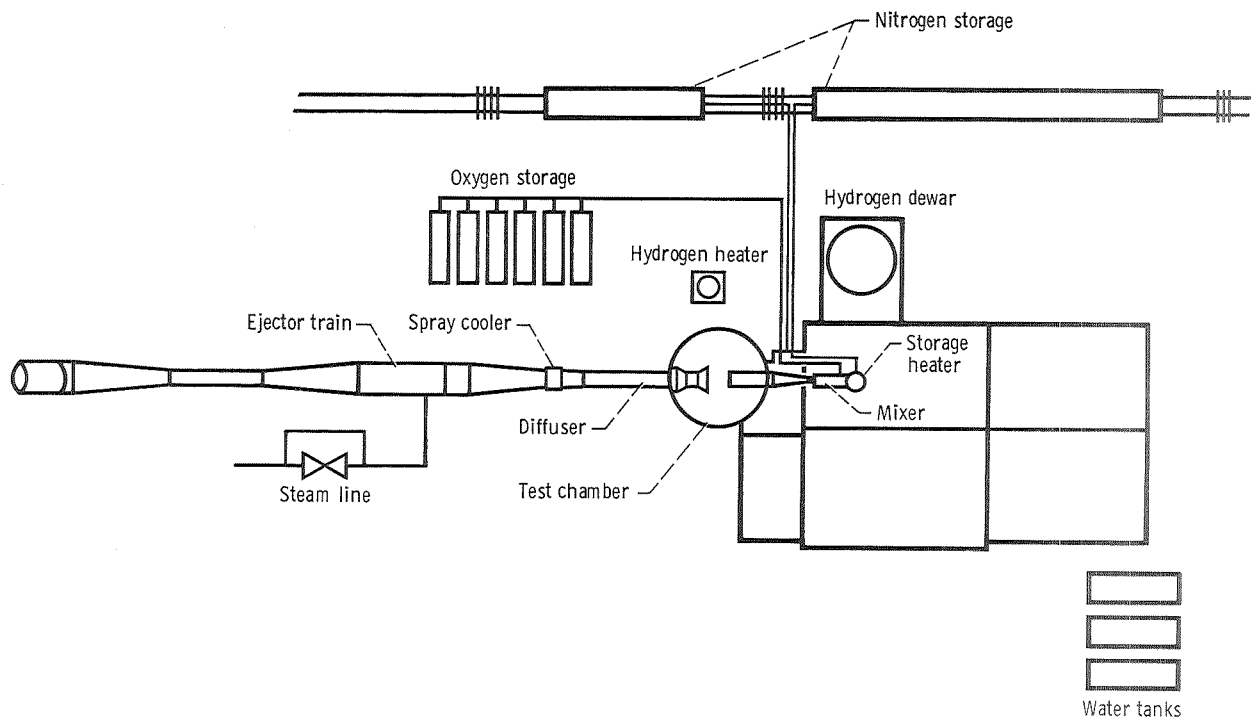


Figure 1. - Schematic layout of hypersonic tunnel facility.

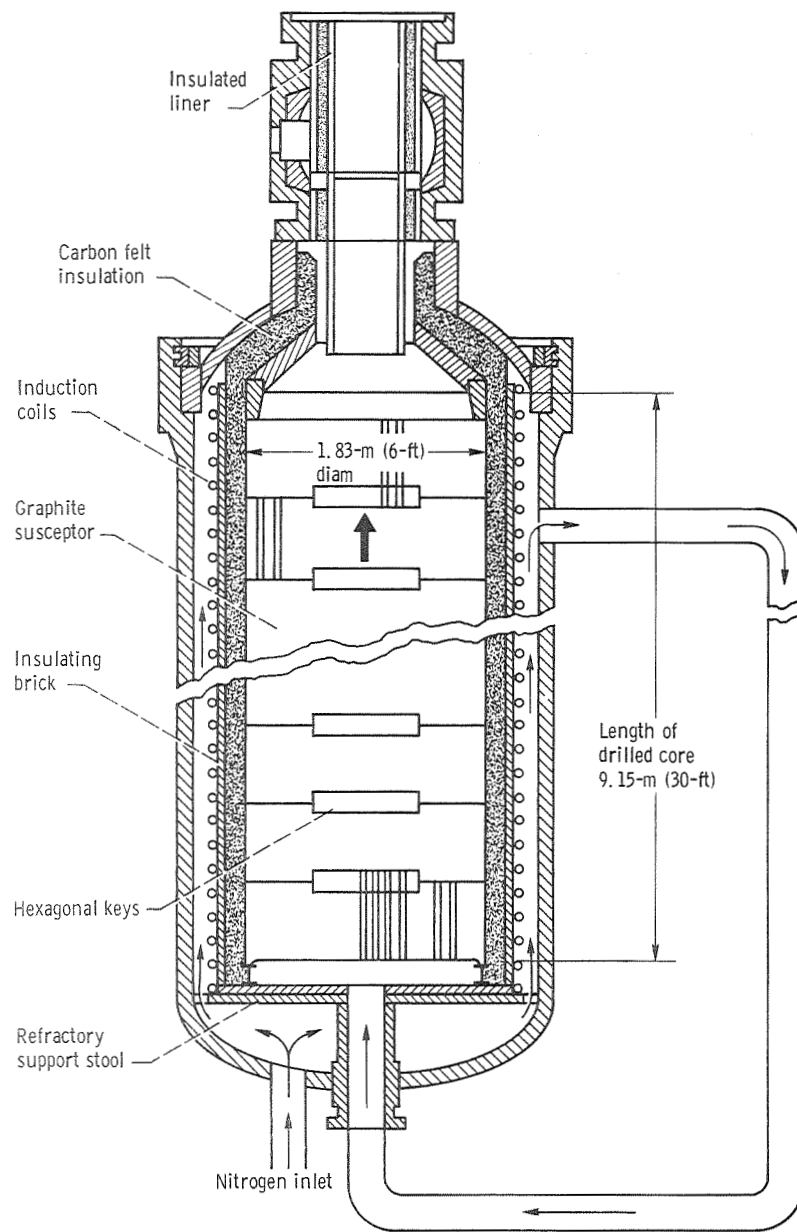


Figure 2. -  $N_2$  heat exchanger graphite drilled core.



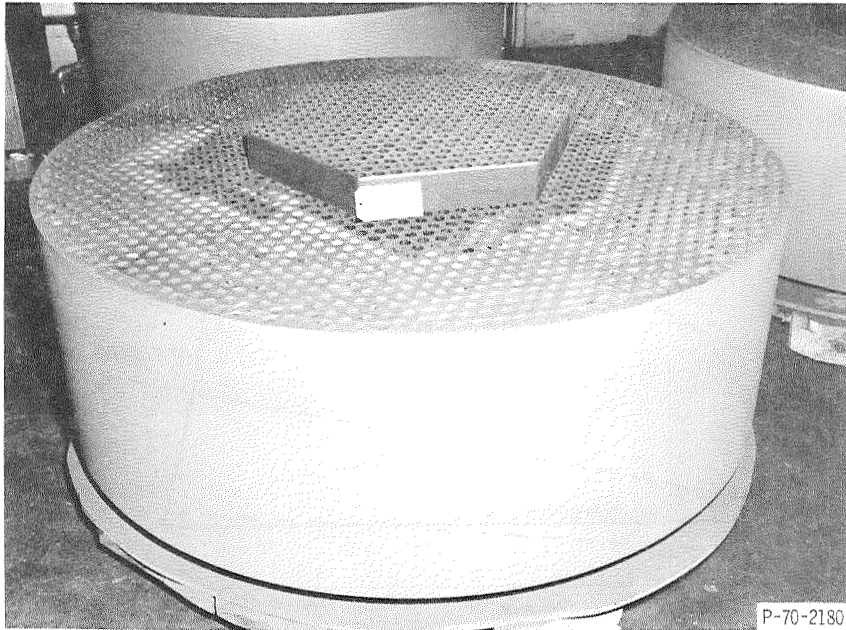


Figure 3. - Typical graphite drilled core section and key block.

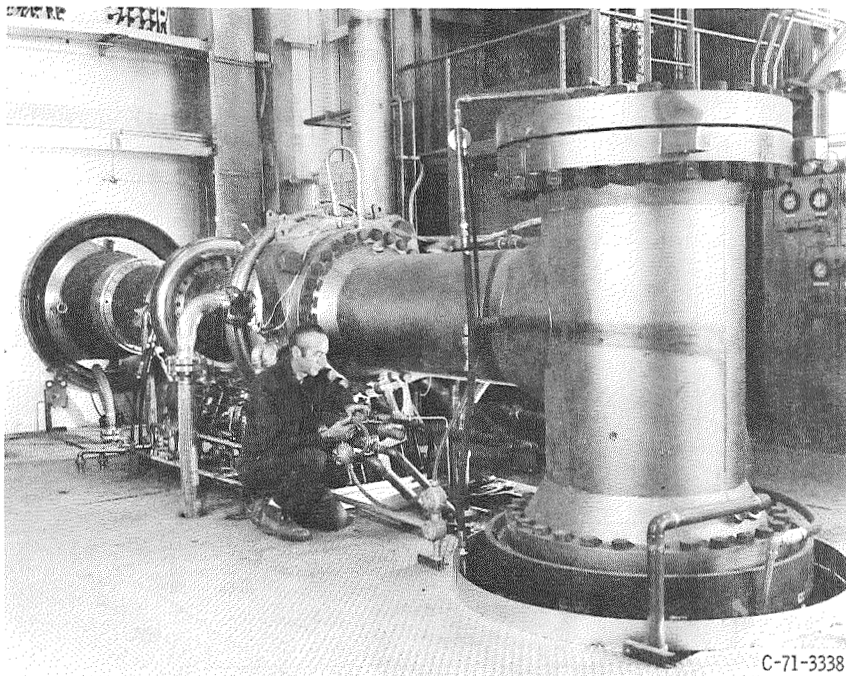
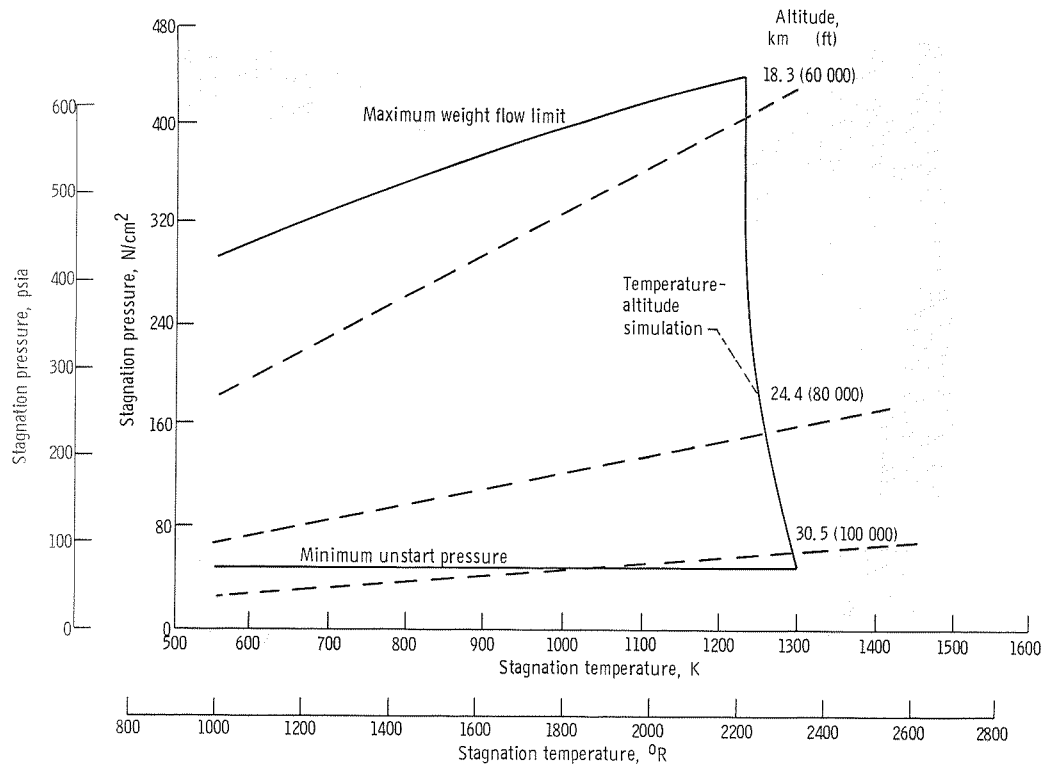
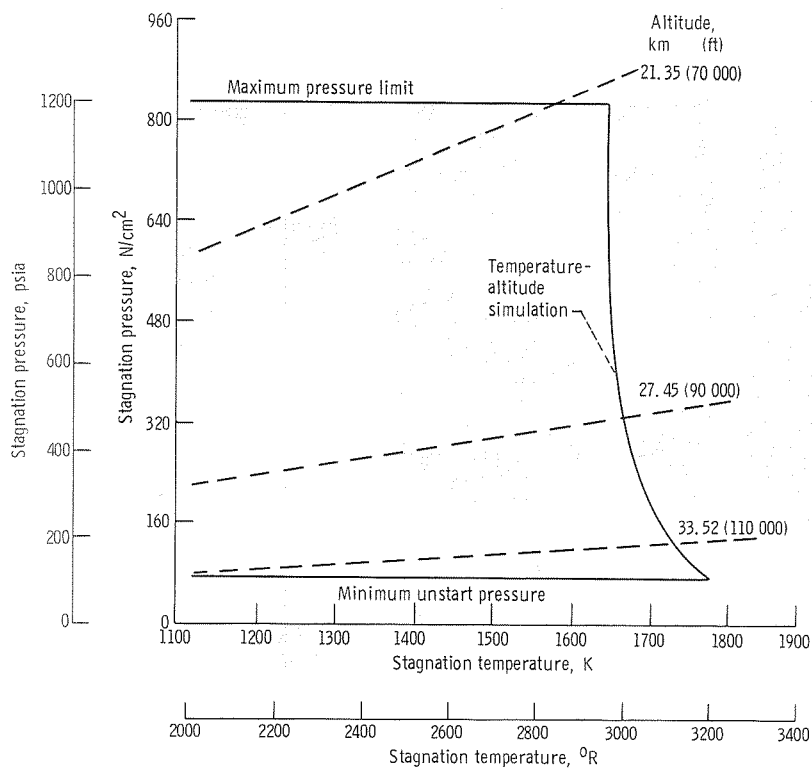


Figure 4. - Facility piping including isolation valve, mixer section, and hypersonic nozzle.



(a) Mach 5.



(b) Mach 6.

Figure 5. - Hypersonic tunnel facility operating range.

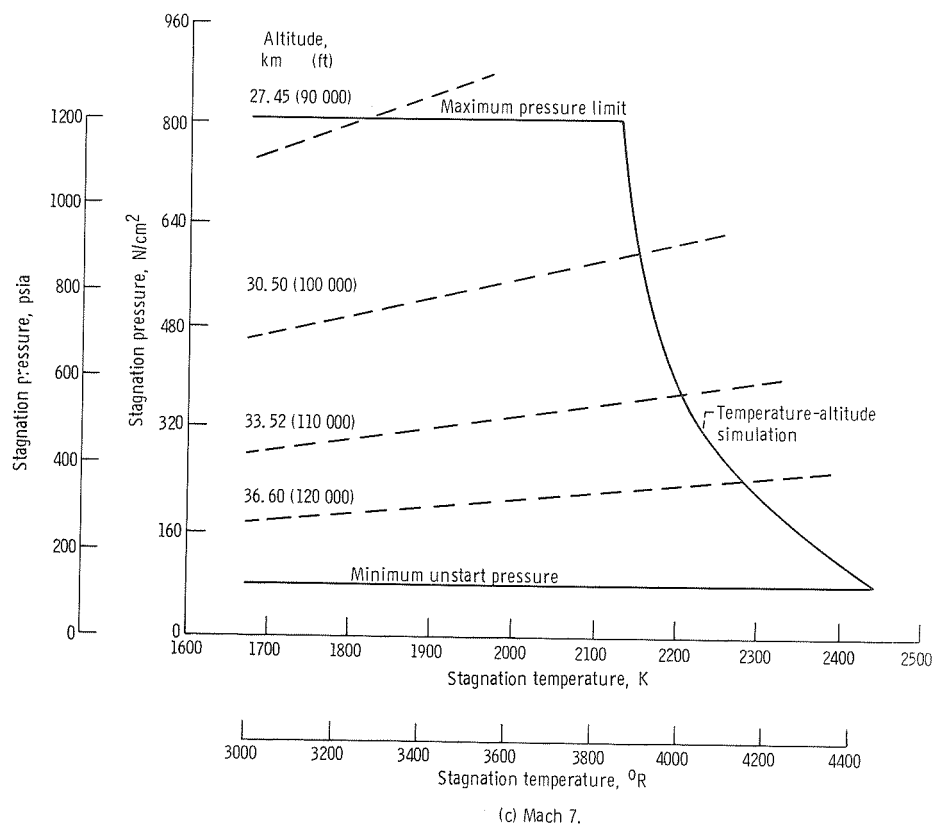


Figure 5. - Concluded.

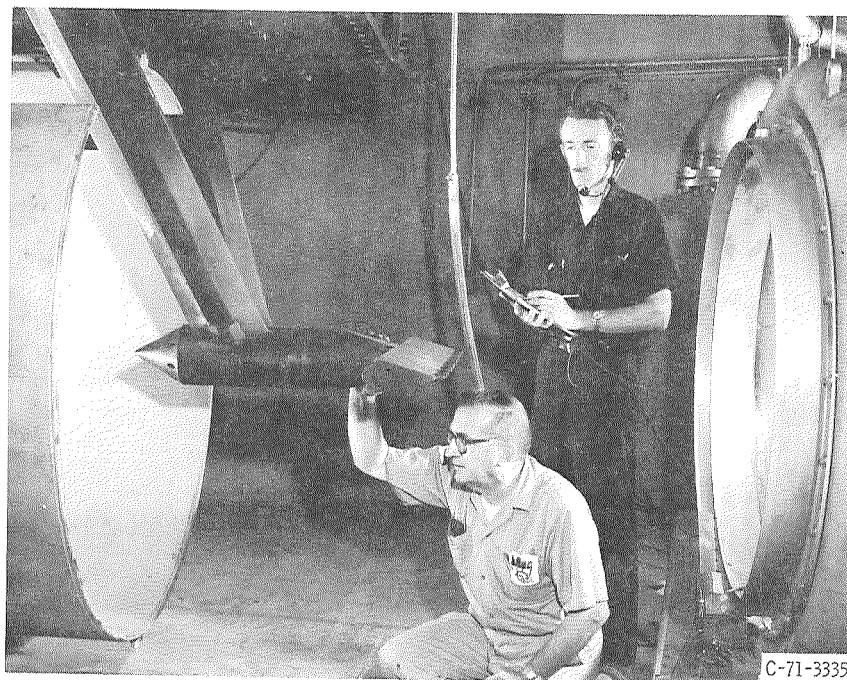


Figure 6. - Calibration rake mounted in test chamber.

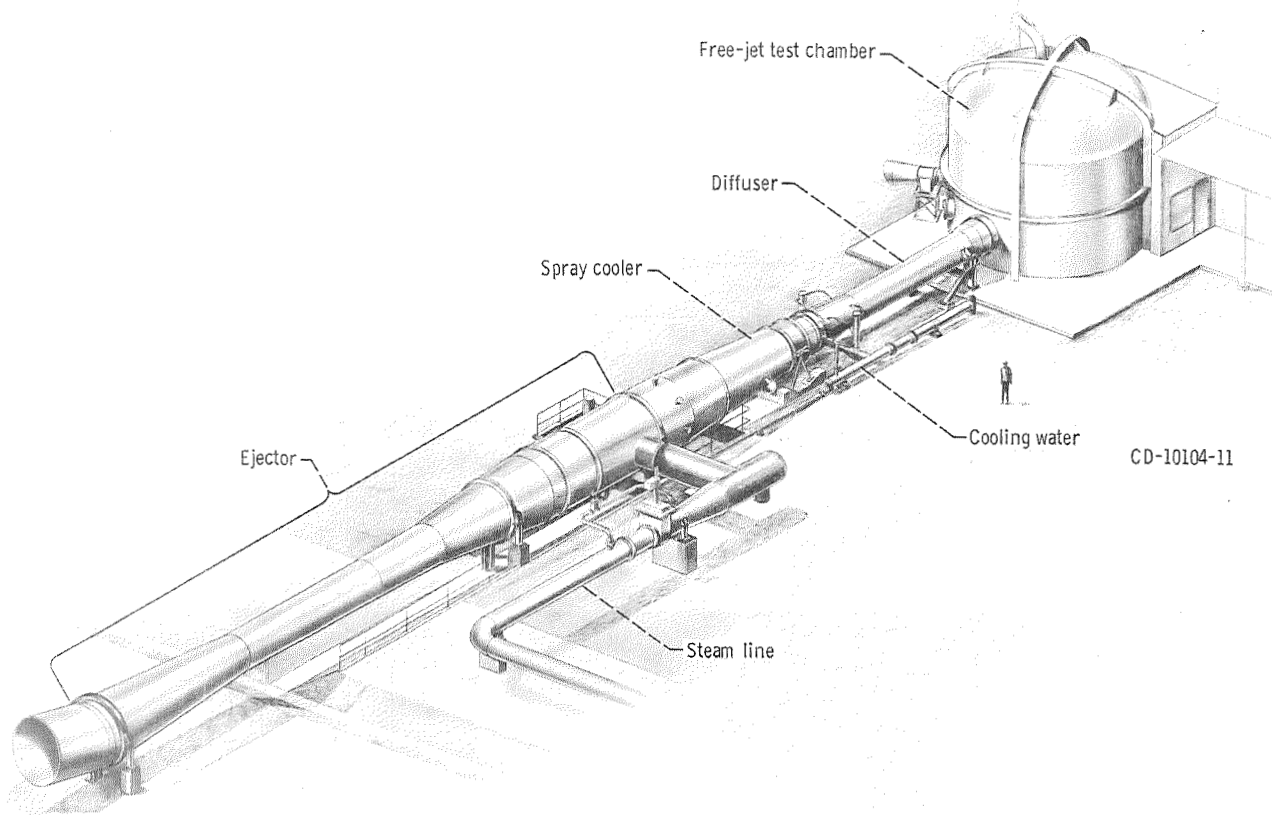


Figure 7. - Hypersonic tunnel facility exhaust system.

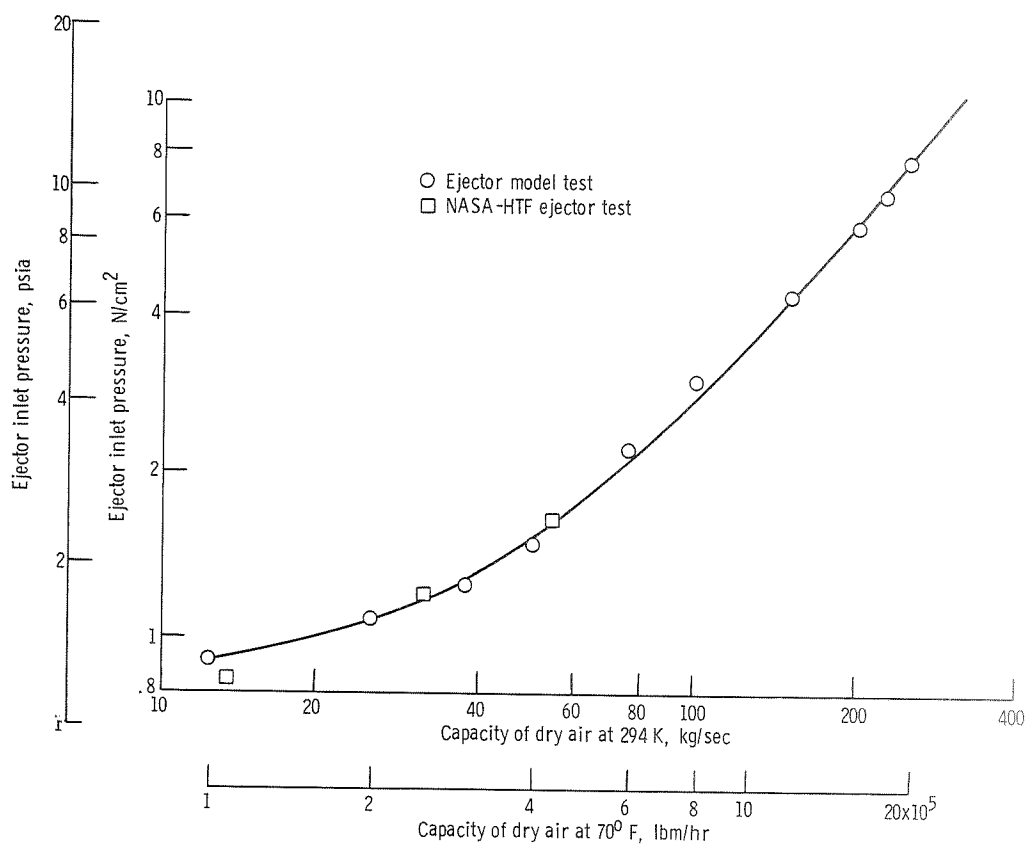


Figure 8. - Steam ejector performance.



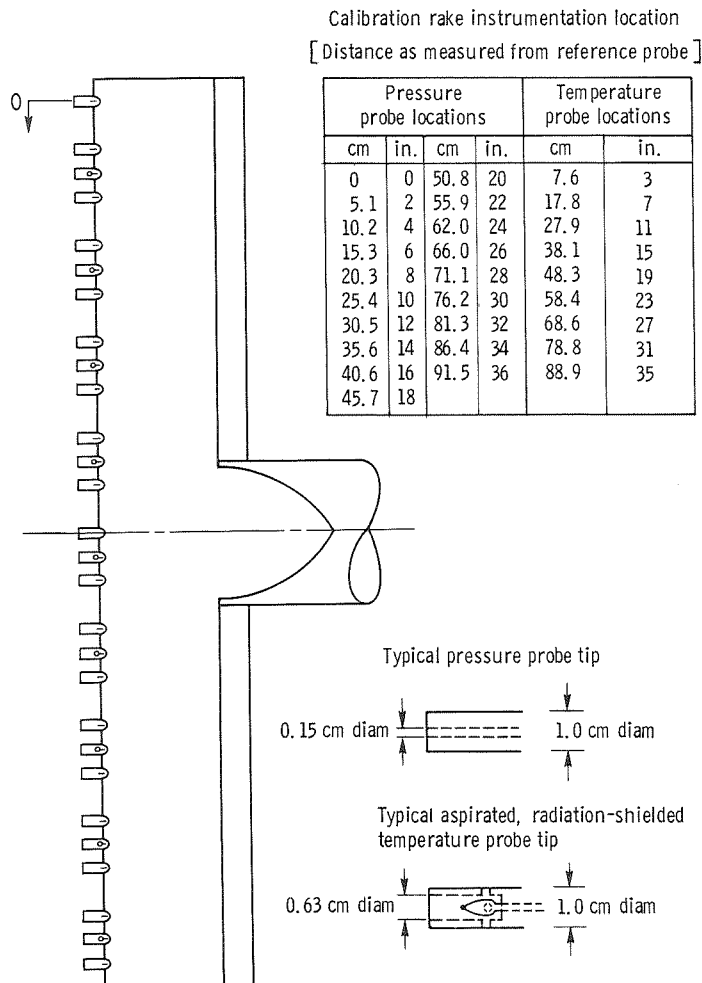


Figure 9. - Calibration rake. Rake in horizontal position - reference probe at left when facing upstream. Rake in vertical position - reference probe at top.

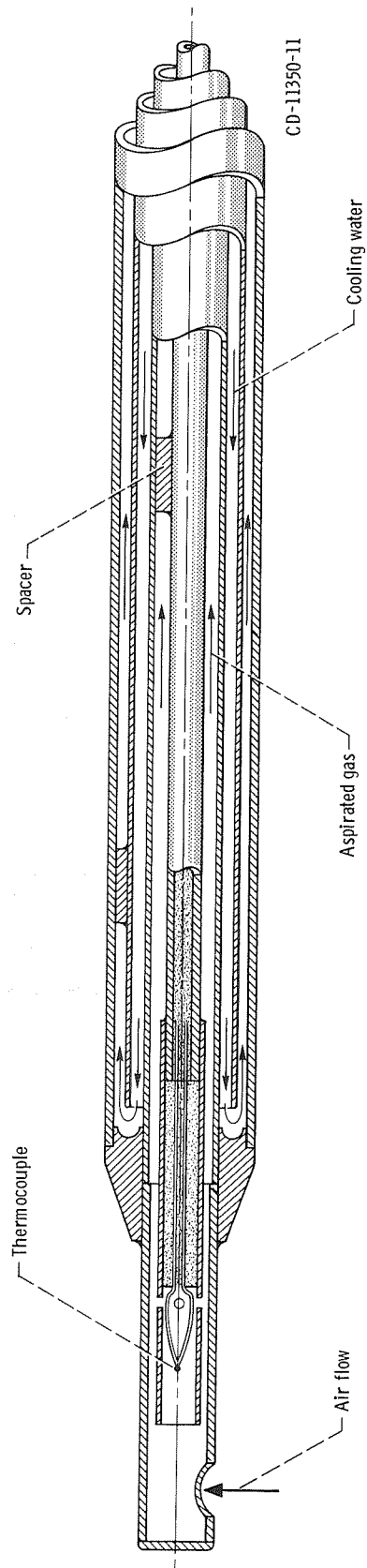


Figure 10. - Aspirated thermocouple probe.

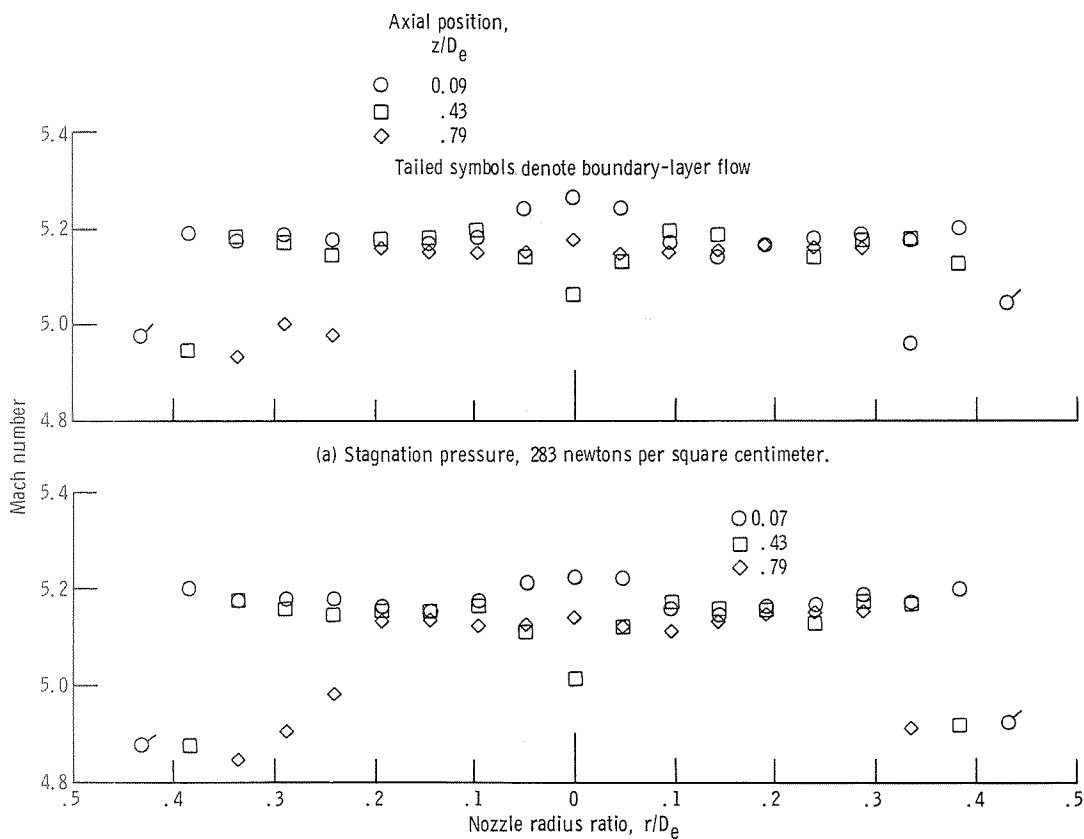
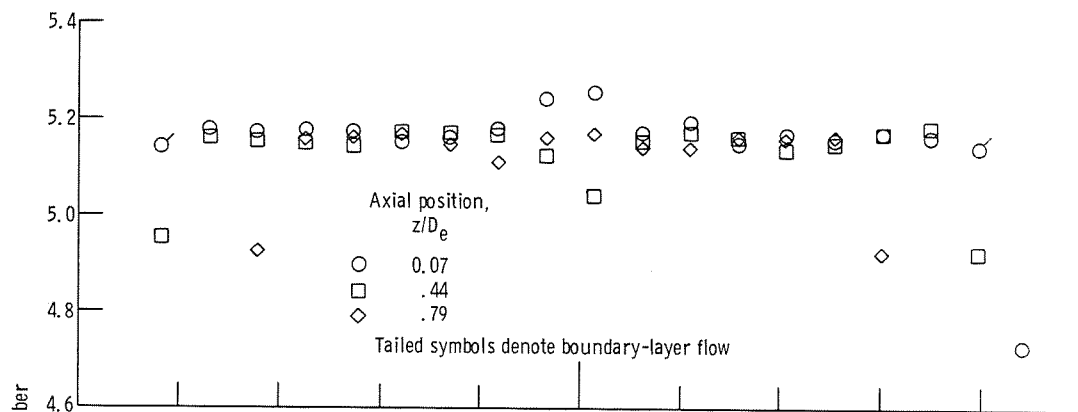
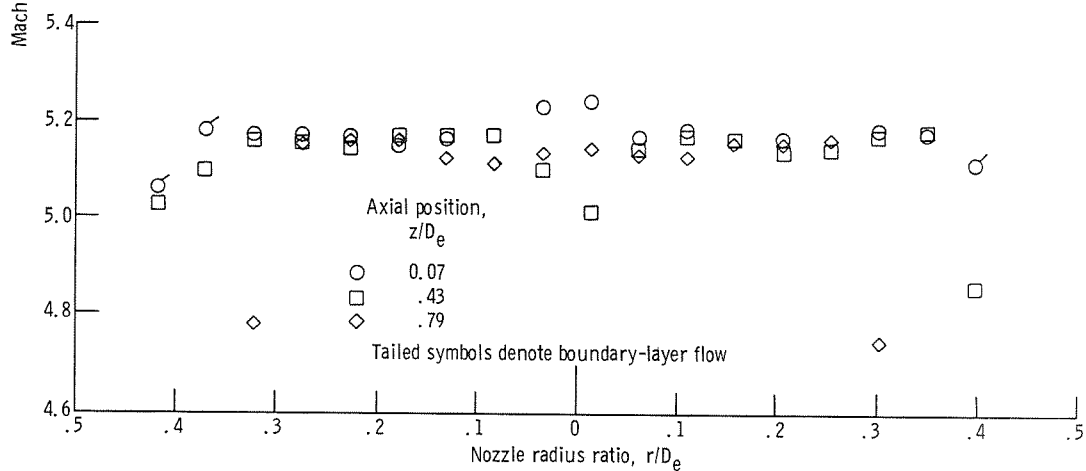


Figure 11. - Radial Mach number profiles in vertical plane; Mach 5 nozzle.



(a) Stagnation pressure, 284 newtons per square centimeter.



(b) Stagnation pressure, 143 newtons per square centimeter.

Figure 12. - Radial Mach number profiles in horizontal plane; Mach 5 nozzle.

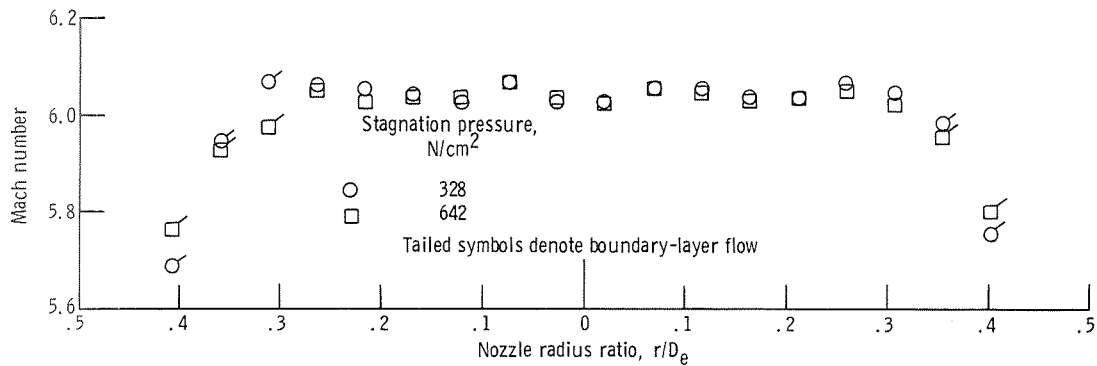
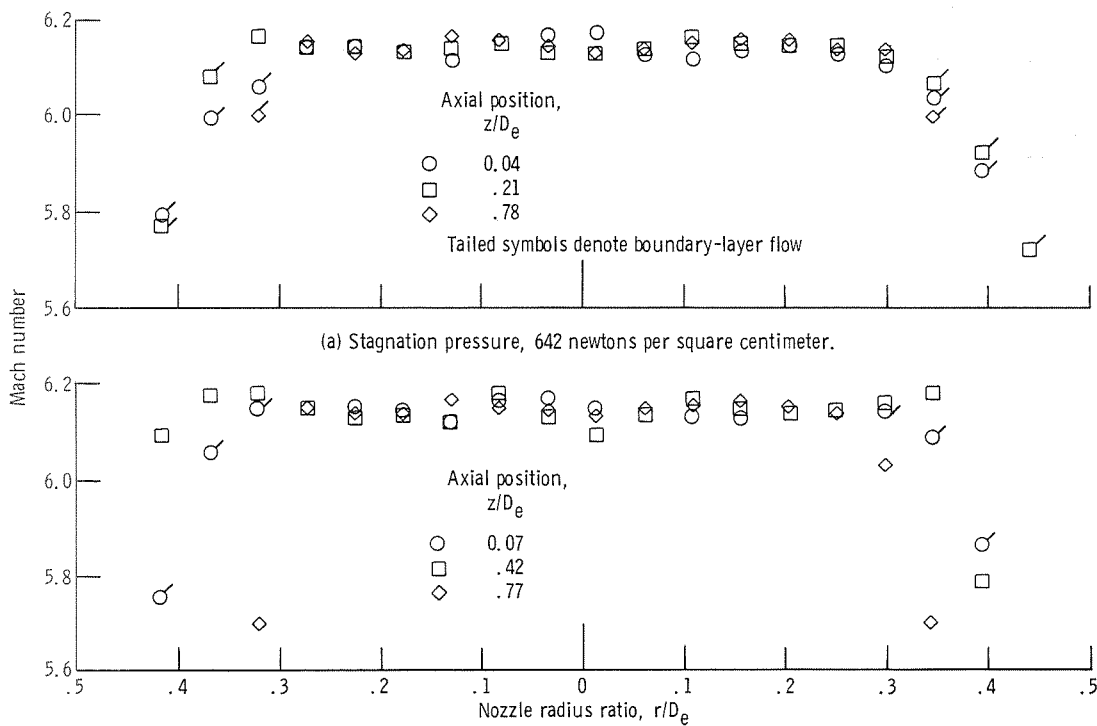


Figure 13. - Radial Mach number profiles. Mach 6 nozzle; simulated air; axial position, 0.06.

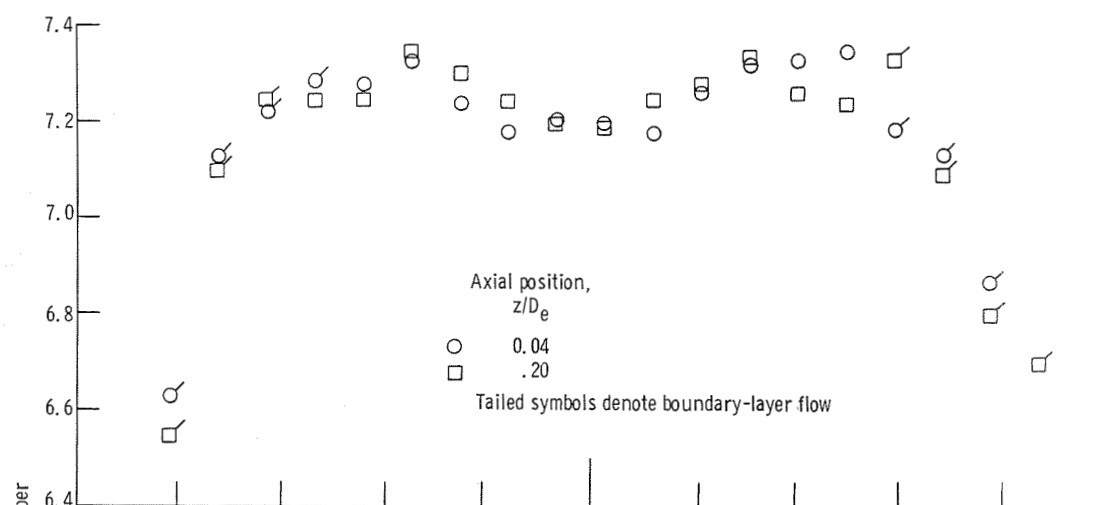


(a) Stagnation pressure, 642 newtons per square centimeter.

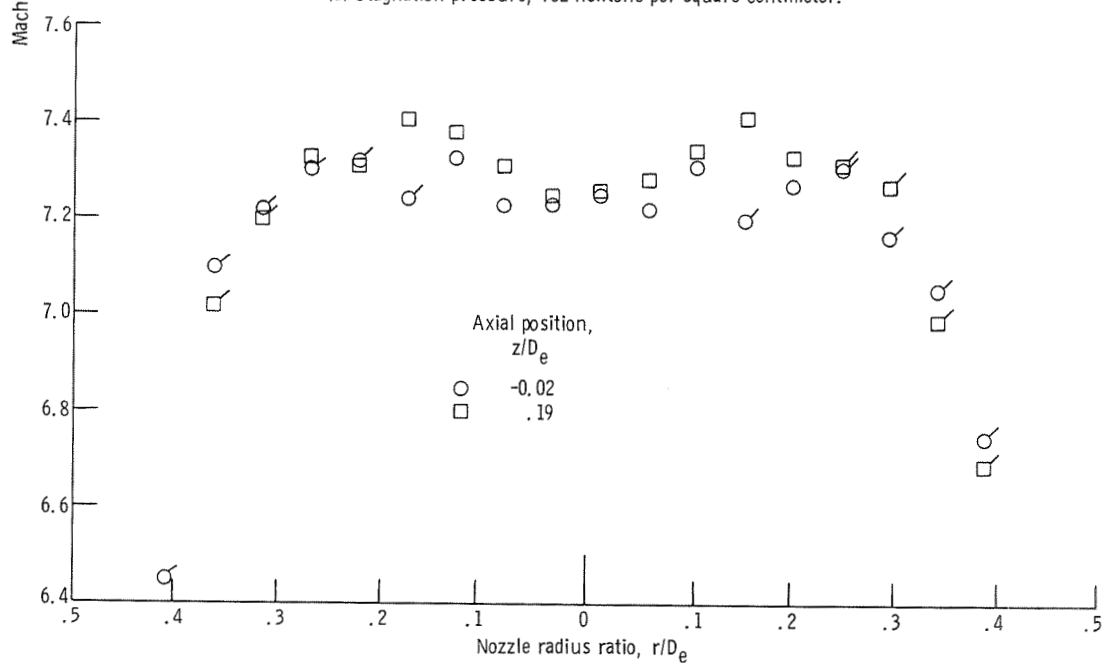
(b) Stagnation pressure, 326 newtons per square centimeter.

Figure 14. - Radial Mach number profiles, Mach 6 nozzle.



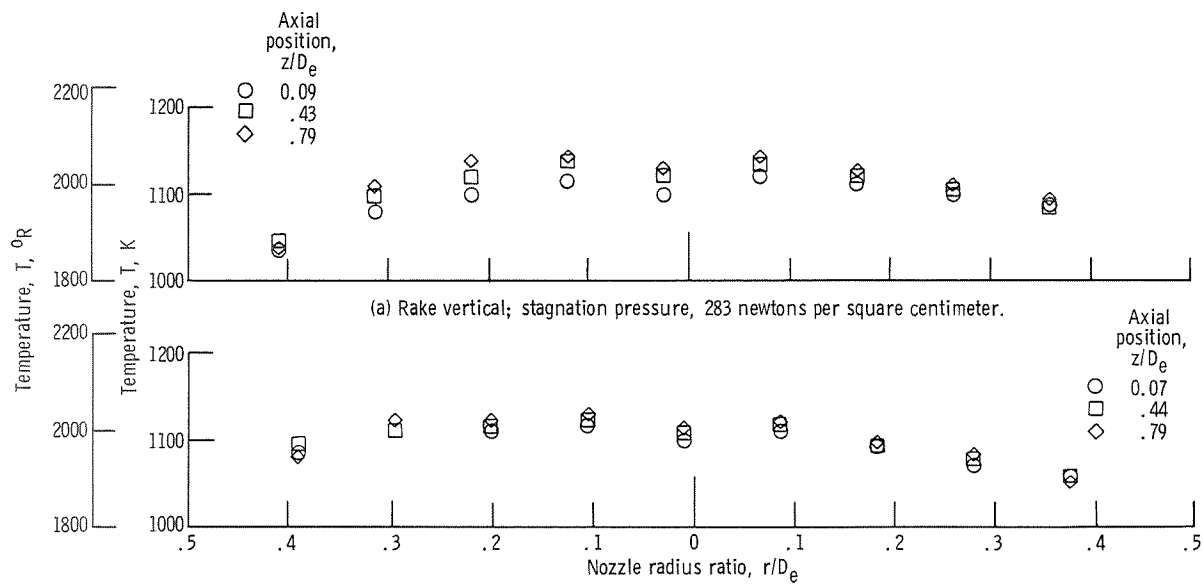


(a) Stagnation pressure, 702 newtons per square centimeter.



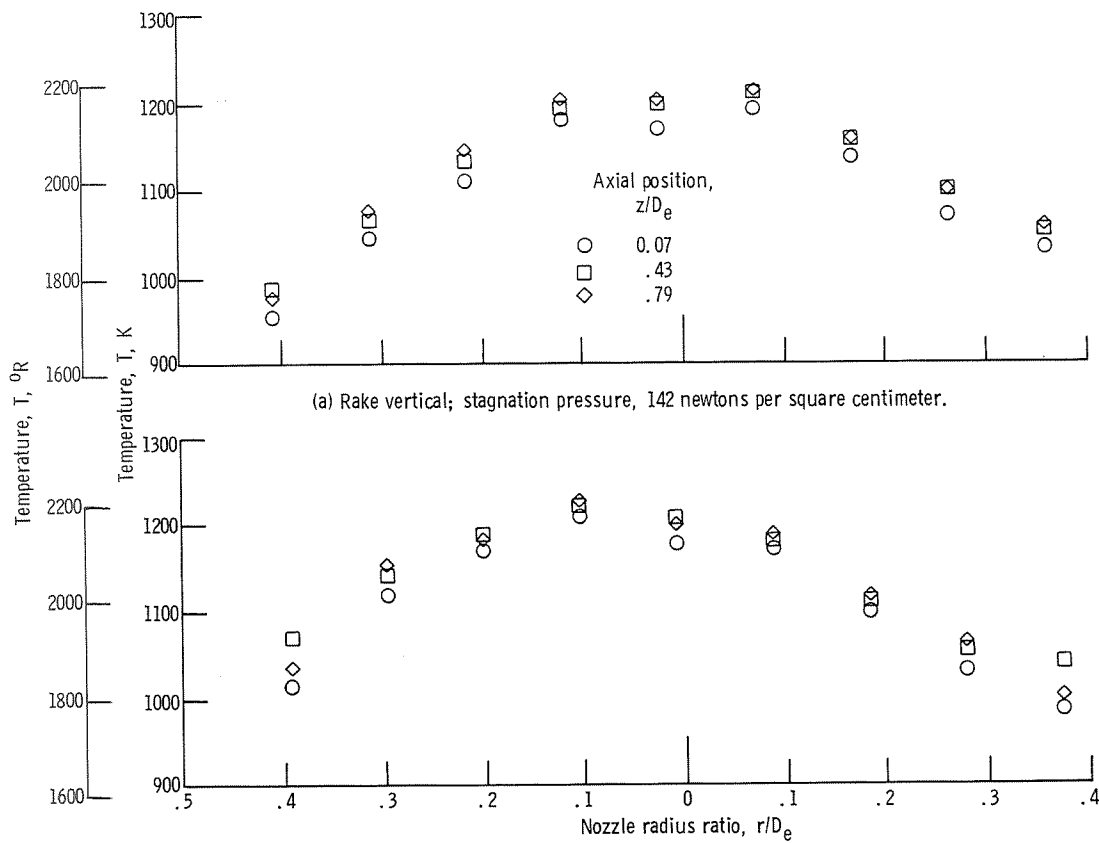
(b) Stagnation pressure, 345 newtons per square centimeter.

Figure 15. - Radial Mach number profiles, Mach 7 nozzle.



(b) Rake horizontal; stagnation pressure, 284 newtons per square centimeter.

Figure 16. - Radial total temperature profiles; Mach 5 nozzle.



(b) Rake horizontal; stagnation pressure, 143 newtons per square meter.

Figure 17. - Radial total-temperature profiles; Mach 5 nozzle.

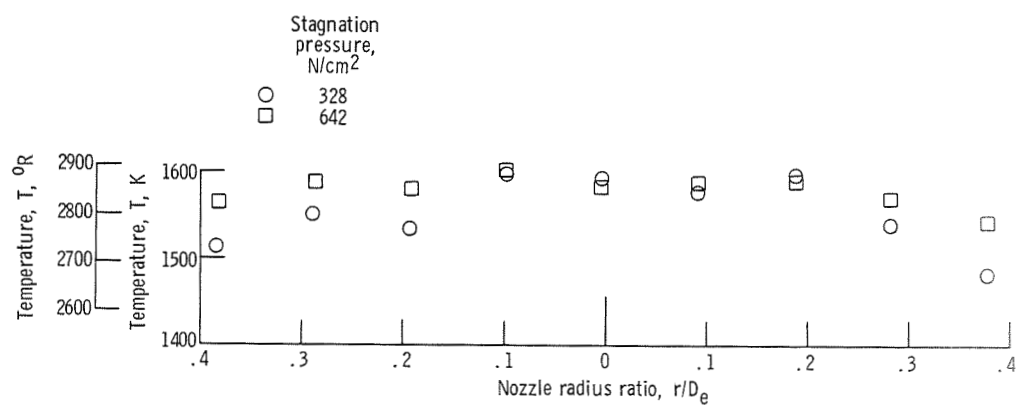


Figure 18. - Radial total temperature profiles. Mach 6 nozzle; simulated air; axial position,  $z/D_e$ , 0.06.

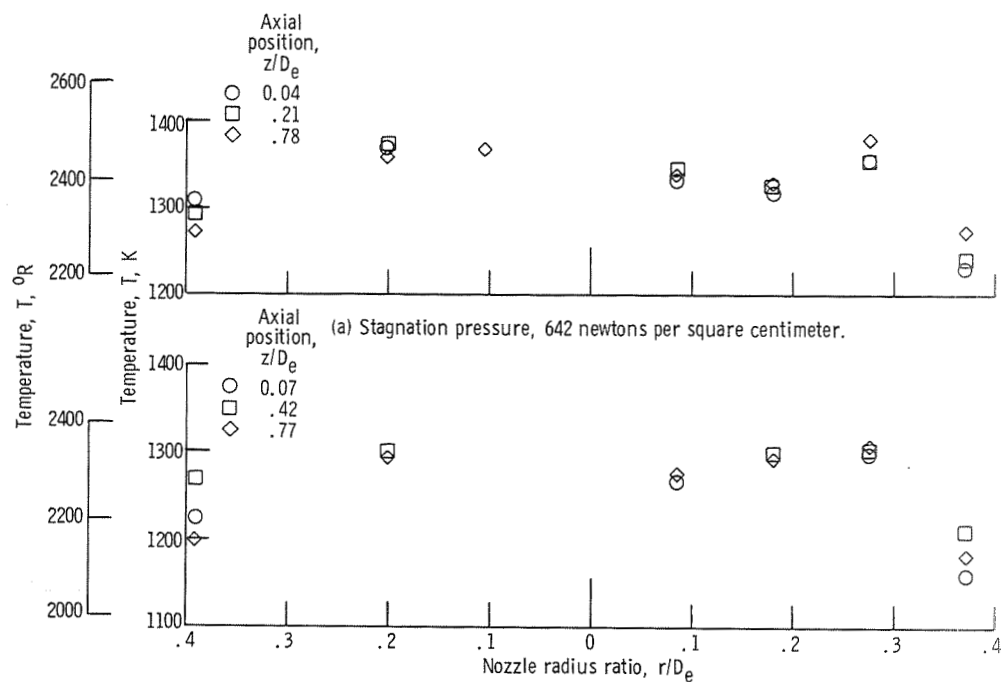


Figure 19. - Radial total temperature profiles; Mach 6 nozzle.

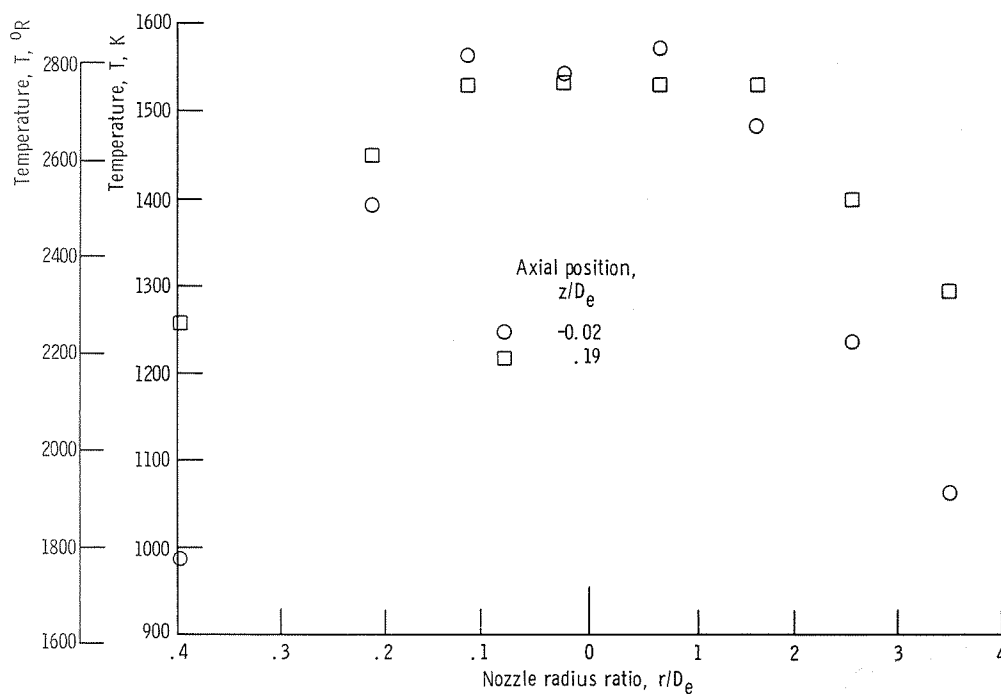
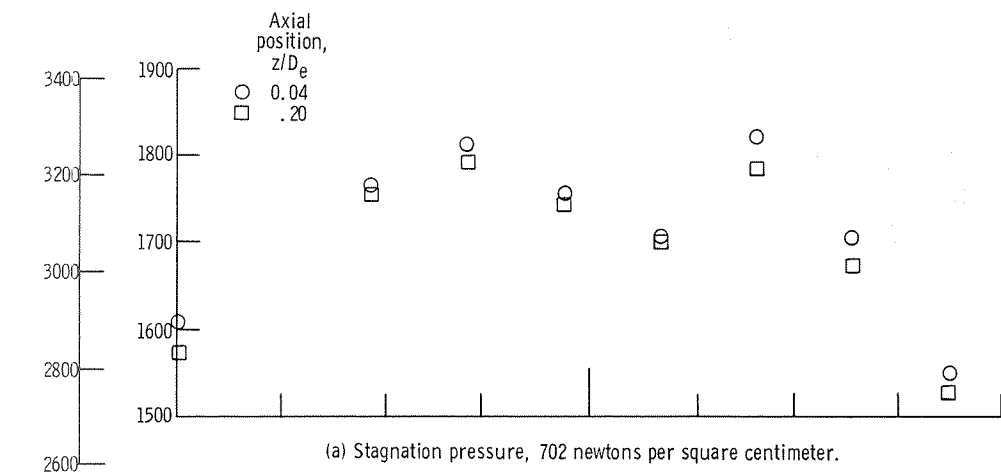


Figure 20. - Radial total temperature profiles; Mach 7 nozzle.

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