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TEST SECTION TEMPERATURE CALIBRATION OF THE AEDC PWT 16-FT TRANSONIC TUNNEL AT STAGNATION TEMPERATURES FROM -30 TO 30°F

G. D. Robson

ARO, Inc.

February 1969

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NOTICES

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FOREWORD

The work reported herein was sponsored by Headquarters, Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), Arnold Air Force Station, Tennessee, in support of Program Element 31014F.

The results of this calibration were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of AEDC, AFSC, Arnold Air Force Station, Tennessee, under Contract F40600-69-C-0001. The calibration was conducted on January 26 and 27, 1968, under ARO Project No. PT0748, and the manuscript was submitted for publication on November 25, 1968.

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This technical report has been reviewed and is approved.

Richard W. Bradley	Roy R. Croy, Jr.
Lt Colonel, USAF	Colonel, USAF
AF Representative, PWT	Director of Test
Directorate of Test	

ABSTRACT

Tests were conducted in the Propulsion Wind Tunnel, Transonic (16T) of the Propulsion Wind Tunnel Facility at the Arnold Engineering Development Center to determine the test section temperature distribution and calibration relationship to a mean nozzle reference temperature while using a cryogenic cooling system to produce stagnation temperatures from -30 to 30°F. Data were obtained over the Mach number range $0.20 \leqq M_\infty \leqq 0.55$ for subsynchronous operation and $0.55 \leqq M_\infty \leqq 1.2$ for synchronous operation. The temperature deviation in a 6- by 6-ft core was found to be less than ±8°F in the stagnation temperature range $-30°F \leqq T_t \leqq 30°F$. It was also determined that an offset calibration factor of -2°F must be applied to the mean nozzle reference temperature to obtain the average test section temperature in a 6- by 6-ft core.

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NOMENCLATURE

M_∞	Free-stream Mach number
p_{ta}	Stilling chamber total pressure, psf
p_{t1}	$\frac{1}{5}\sum_{i=1}^{5} p_{ti}$, Mean total pressure from test section total pressure probes, psf
Re	Reynolds number
T_g	Measured gas temperature (See Appendix II), °R
T_t	True total temperature (See Appendix II), °R
$T_{t,a}$	Mean total temperature from primary core thermocouple array in nozzle contraction region (See Fig. 6a), °F
$T_{t,b}$	Mean total temperature from secondary thermocouple array in nozzle contraction region (See Fig. 6a), °F
$T_{t,1}$	Mean total temperature from primary core thermocouple array in test section (See Fig. 6b), °F
$T_{t,2}$	Mean total temperature from secondary thermocouple array in test section (See Fig. 6b), °F
ΔT	Difference between mean temperature and temperature of individual thermocouples in a selected array, °F
Δ	Recovery-correction factor for total pressure (See Appendix II)
Δ_o	Recovery-correction factor for Mach number (See Appendix II)
δ	Temperature calibration parameter, $T_{t,1} - T_{t,a}$, °F
θ_w	Test cart wall angle (positive when walls are diverged), deg

SECTION I
INTRODUCTION

The addition of a cryogenic cooling system, in December 1967, expanded the temperature matching capabilities of the Propulsion Wind Tunnel Facility Tunnel 16T at the Arnold Engineering Development Center (AEDC). A calibration was performed to determine the extended region of matched temperature and subsequent relationships between test section temperature and a mean nozzle reference temperature while using a cryogenic cooling system to produce stagnation temperatures from -30 to 30°F.

A secondary mission of the calibration was the development of procedures for subsynchronous operation of the compressor drive to reliably achieve stable operation in the Mach number range $0.2 \leqq M_\infty \leqq 0.55$ for a limited range of test section pressures.

The results of the calibration using the cryogenic cooling system and subsynchronous operation of the compressor are presented in this report.

SECTION II
APPARATUS

2.1 BASIC TUNNEL AND SUPPORT EQUIPMENT

Tunnel 16T is a continuous flow, closed-circuit tunnel with a Mach number range from 0.55 to 1.60 while operating the tunnel compressor in the synchronous mode (600 rpm). The Mach number range can be extended by operating in a subsynchronous mode (less than 600 rpm). The tunnel is capable of operating in a stagnation pressure range from approximately 80 to 4000 psfa. The stagnation temperature range, using water in the tunnel cooler, extends from approximately 80 to 160°F, depending on the time of year. This range can be extended, by use of cryogenically chilled coolant in the tunnel cooler and injection of liquid air into the tunnel airstream, to approximately -30°F. A structural limitation on some tunnel components limited the test section temperature to -30°F.

The removable test section is 16 ft square and 40 ft long. A 9-ft tapered porosity section connects the two-dimensional, solid-plate, flexible nozzle to the porous wall test section. The test section walls have 60-deg inclined holes and a porosity of 6 percent. Plenum suction for Tunnel 16T is provided by the Plenum Evacuation System (PES), and additional suction is available by adjustment of movable diffuser flaps.

The location of Tunnel 16T in the PWT complex is shown in Fig. 1, Appendix I. The associated cryogenics system is also shown adjacent to Tunnel 16T in this figure. Detailed information on the tunnel can be found in Refs. 1 and 2.

2.2 CRYOGENIC COOLING SYSTEM

The Tunnel 16T cryogenic cooling system is basically composed of a liquid nitrogen system to chill the mineral spirits for the tunnel cooler and a liquid air system for direct injection of cryogenics into the tunnel airstream. A photograph of the liquid air injection spray bars in the tunnel stilling chamber is presented in Fig. 2. The spray bar system is removed when this testing capability is not desired, and reinstalled upon request.

2.3 TEST APPARATUS

Thermocouples used in the temperature calibration were shielded copper-constantan aligned with the airstream. The basic dimensions of a typical thermocouple are given in Fig. 3.

Two thermocouple grids were built for the calibration. Both grids were constructed by safety-wiring the thermocouples to two sets of parallel prestressed steel cables located in the nozzle contraction region and in the test section (Figs. 4 and 5). Two grids were needed to obtain a test section temperature calibration as a function of the temperature in the nozzle contraction region. This was necessary because a reference was needed to enable test conditions to be accurately set in the test section after the test section thermocouple grid was removed. The geometry of the two grids is shown in Fig. 6. Photographs of the tunnel installations are shown in Fig. 7.

In addition to the thermocouples, total pressure probes were mounted on the two thermocouple grids. The pressure probes were made from 0.125-in.-OD by 0.018-in.-wall stainless steel tubing. One probe was mounted on the nozzle grid and five were mounted on the test section grid.

Three electrical counters for measuring compressor speed capable of measuring one-third rpm per count were located in the compressor monitoring room, in the compressor control room, and in the 16T control room.

SECTION III
PROCEDURE

3.1 SUBSYNCHRONOUS OPERATION

The Tunnel 16T compressor is normally operated in a synchronous mode (i.e., compressor speed = 600 rpm). Mach number is normally set by varying the nozzle contour and by controlling the tunnel pressure ratio with stator blade adjustment. However, Mach numbers below 0.55 are set by employing the basic Mach 1 nozzle contour and by controlling tunnel pressure ratio (varying the speed of the wound-rotor induction motors used to drive the compressor). The motor speed can be accurately controlled to one-third rpm in this subsynchronous mode which allows Mach numbers in the range $0.2 \leqq M_\infty \leqq 0.55$ to be set with little more difficulty than encountered in normal synchronous operation.

3.2 TEMPERATURE CALIBRATION PROCEDURE

During the temperature calibration, the temperature distribution at station 12.2 in the test section was studied as a function of the distribution at station -64.25 in the nozzle contraction region. The nozzle grid shown in Fig. 6a was broken up into two groups of thermocouples denoted as $T_{t,a}$ and $T_{t,b}$. The test section grid was also broken up into two groups to measure temperatures designated as $T_{t,1}$ and $T_{t,2}$ as shown in Fig. 6b. Groups $T_{t,1}$ and $T_{t,a}$ were selected so that thermocouples from both groups would be contained in approximately the same stream tube.

When a given Mach number and altitude were selected, the corresponding matched temperature was set by passing chilled mineral spirits through the tunnel cooler and, if necessary, by injecting liquid air into the tunnel airstream. Once the matched temperature was set, distortion and calibration parameters were determined. Also, the total pressure was studied to see if there was an appreciable pressure change from the nozzle to the test section.

3.3 DATA REDUCTION PROCEDURE

Data obtained during the calibration were reduced on line using a Raytheon 520 computer and recorded on a line printer in the Tunnel 16T control room. The data recorded included individual temperature and pressure readings, temperature and pressure differentials, and average temperatures. For monitoring purposes during operation, a cathode ray tube (CRT) was used to display the ΔT between the mean temperatures and the temperature of the individual thermocouples of a selected group.

The calibration factor (δ) was determined by correlating the temperature from the permanently installed nozzle grid with the temperature from the temporary grid in the test section. Temperature values from thermocouple groups $T_{t,a}$ and $T_{t,1}$ were used to obtain this parameter because they represent the temperature of a 6- by 11-ft core in the nozzle and a 6- by 6-ft core in the test section, respectively. Corrections for Reynolds number and Mach number effects (Appendix II) were applied to the measured temperatures before δ was determined. The thermocouples of the arrays designated as $T_{t,b}$ and $T_{t,2}$ were used to develop the data presented in Fig. 8. Thermocouples of the type used in this calibration are generally considered to have a systematic error of ±4°F.

A check made to determine if there was a total pressure loss between the nozzle and the test section as a result of the installation of the cryogenic sprays revealed no pressure deviation between p_{ta} and p_{t1}; therefore, a pressure correction was not required for data reduction purposes.

SECTION IV
RESULTS AND DISCUSSION

One of the results of primary interest was the temperature calibration parameter linking the nozzle temperature to the test section temperature. After the thermocouple corrections were applied to the raw temperature data, the calibration parameter was determined to be -2°F. Therefore, to obtain a given test section temperature, the nozzle temperature had to be set two degrees lower than the desired test section temperature. Temperature could be controlled to within ±1°F of the desired test section temperature.

Temperature profiles illustrating the temperature distribution in the nozzle and test section in the form of isolines are shown in Fig. 8. All temperatures have been corrected for Mach number and Reynolds number effects. The isoline method of presentation was selected because it provides a means of physically depicting the temperature distribution in the test section and nozzle as a function of $T_{t,1}$. Deviation in the temperature profiles of Fig. 8 was found to be less than ±8°F for a 6- by 6-ft test section core. Thermocouples on corresponding stream tubes in the contraction region produced similar results, thereby allowing a nearly one-to-one correlation to be made while testing without the test section thermocouple grid.

Installation of the cryogenics system extended the testing capability of the PWT Tunnel 16T. Regions of matched temperature for standard day conditions are presented in the operating envelope of Fig. 9. The limits indicated for temperature matching are governed by exhauster capacity for synchronous operation and power limits of the wound rotor induction motors for subsynchronous operation. Subsynchronous operation may be time limited by the heat capacity of the liquid rheostats used to control the wound-rotor induction motors.

The normal operating envelope of Tunnel 16T (Ref. 1) extends from $0.2 \leqq M_\infty \leqq 1.6$. However, since Fig. 9 was designed to illustrate the temperature matching capabilities created by the cryogenics system, the Mach number range was not extended beyond the region for which extrapolation of data was considered reasonable.

The Reynolds number envelope for the extended matched temperature range is presented in Fig. 10.

SECTION V
CONCLUSIONS

The following conclusions were made after temperature calibration of the PWT Tunnel 16T with the cryogenic cooling system installed:

1. A temperature calibration factor of $\delta = -2°F$ must be applied to the nozzle temperature to obtain the correct test section temperature.
2. The temperature deviation in the test section was less than ±8°F for a 6- by 6-ft core. An approximate one-to-one correlation was found to exist between the test section temperature deviation and the deviation of the temperatures in the nozzle contraction region so that the nozzle parameter could be used to predict test section conditions when testing without the test section thermocouple grid.
3. Temperature control can be held within ±1°F of the desired test section temperature.
4. Subsynchronous operation of Tunnel 16T is feasible and productive.

REFERENCES

1. Test Facilities Handbook (Seventh Edition). "Propulsion Wind Tunnel Facility, Vol. 5." Arnold Engineering Development Center, July 1968.

2. Gunn, J. A. "Check Calibration of the AEDC 16-Ft Transonic Tunnel." AEDC-TR-66-80 (AD633277), May 1966.

3. Riddel, J. F. "Performance and Operating Characteristics of the AEDC 16-Ft Transonic Tunnel Low Stagnation Temperature System." (Unpublished AEDC Technical Report).

4. Glawe, George E., Simmons, Frederick S., and Stickney, Truman M. "Radiation and Recovery Corrections and Time Constants of Several Chromel-Alumel Thermocouple Probes in High-Temperature, High-Velocity Gas Streams." NACA-TN-3766, October 1956.

APPENDIXES

I. ILLUSTRATIONS
II. THERMOCOUPLE CORRECTIONS

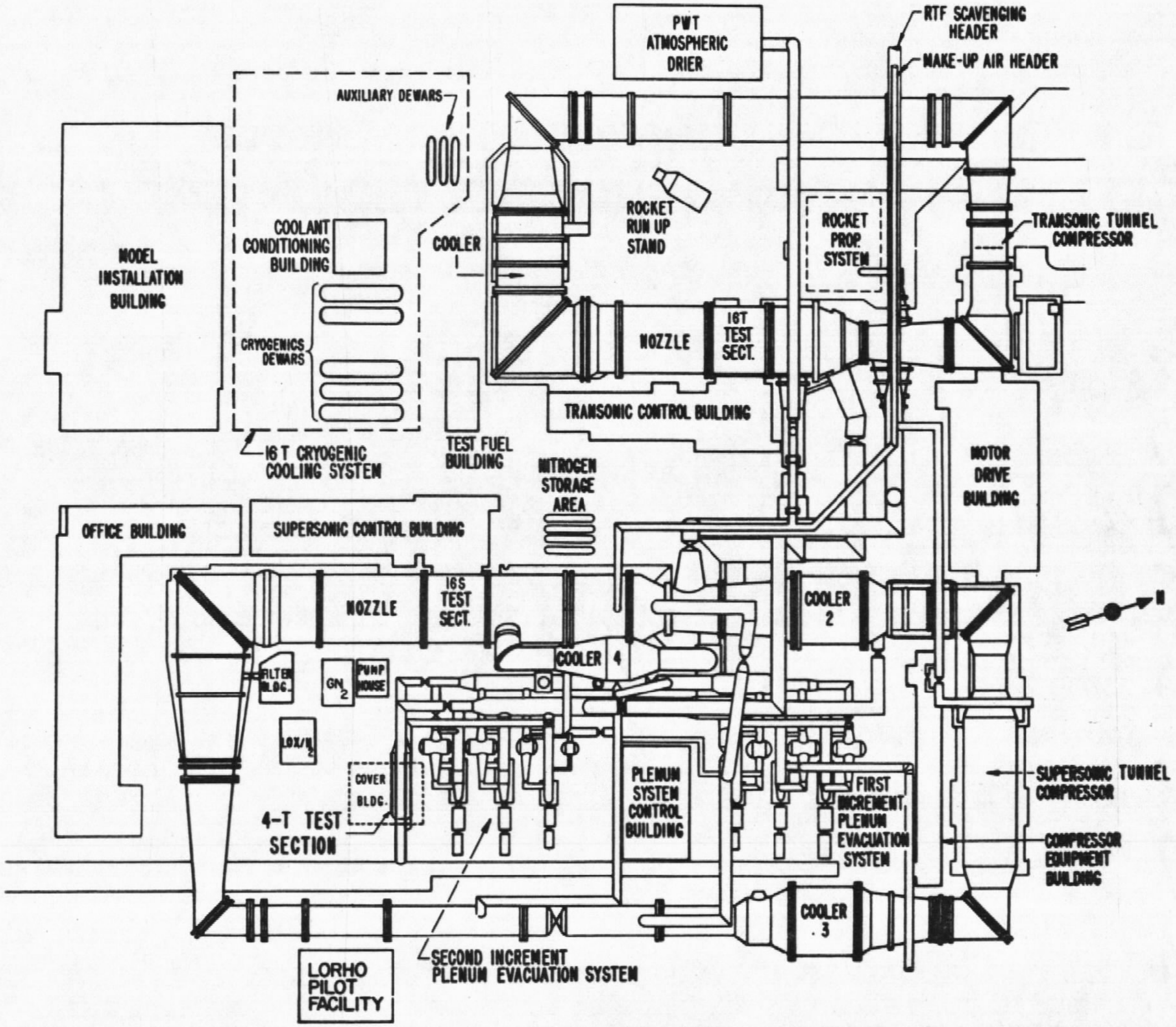


Fig. 1 PWT Facility Layout

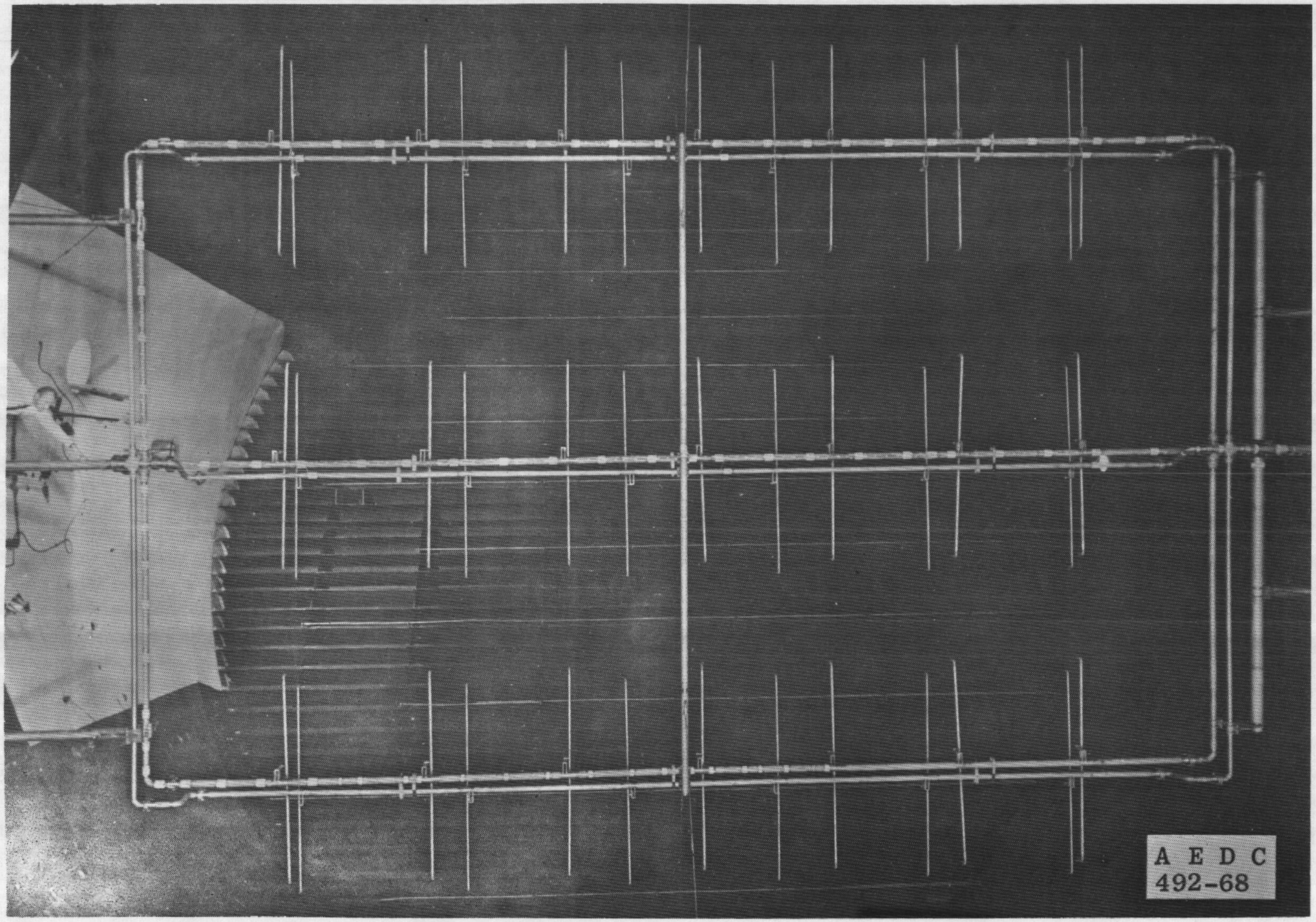
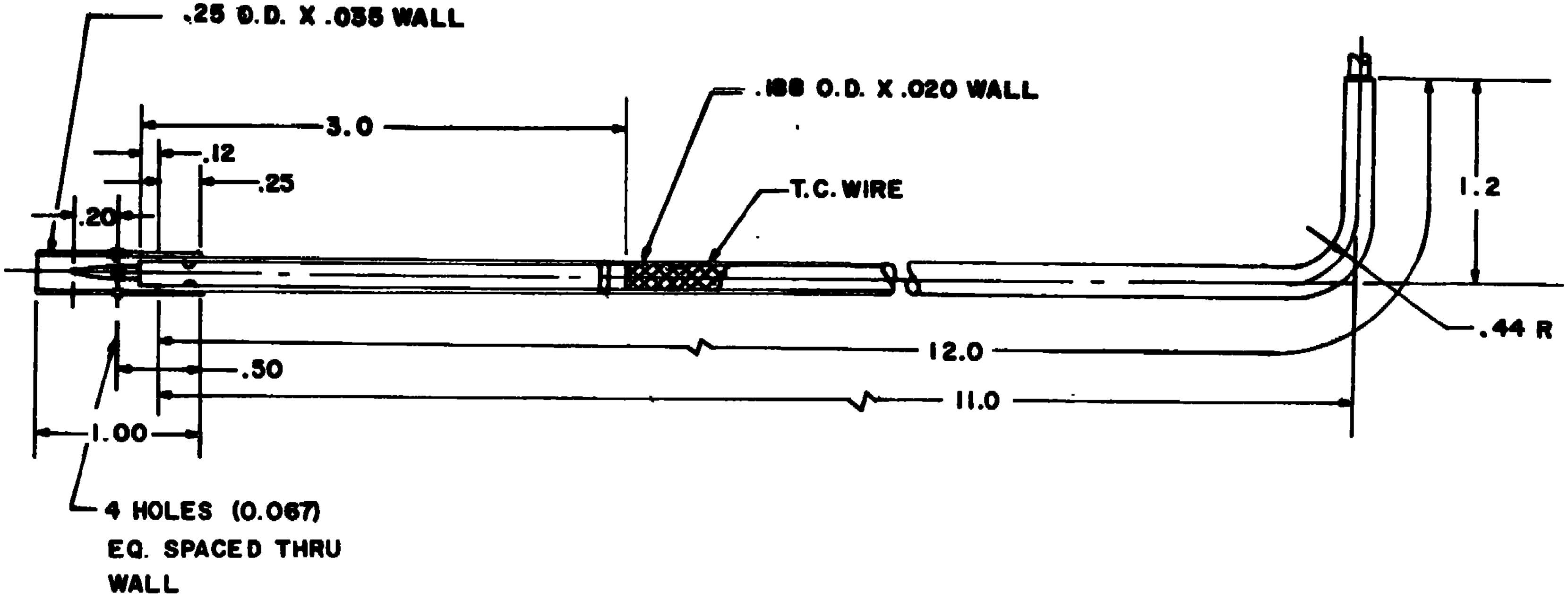


Fig. 2 Liquid Air Injection Spray Bars in Tunnel 16T Stilling Chamber



NOTE: ALL DIMENSIONS
IN INCHES

Fig. 3 Geometry of a Typical Thermocouple

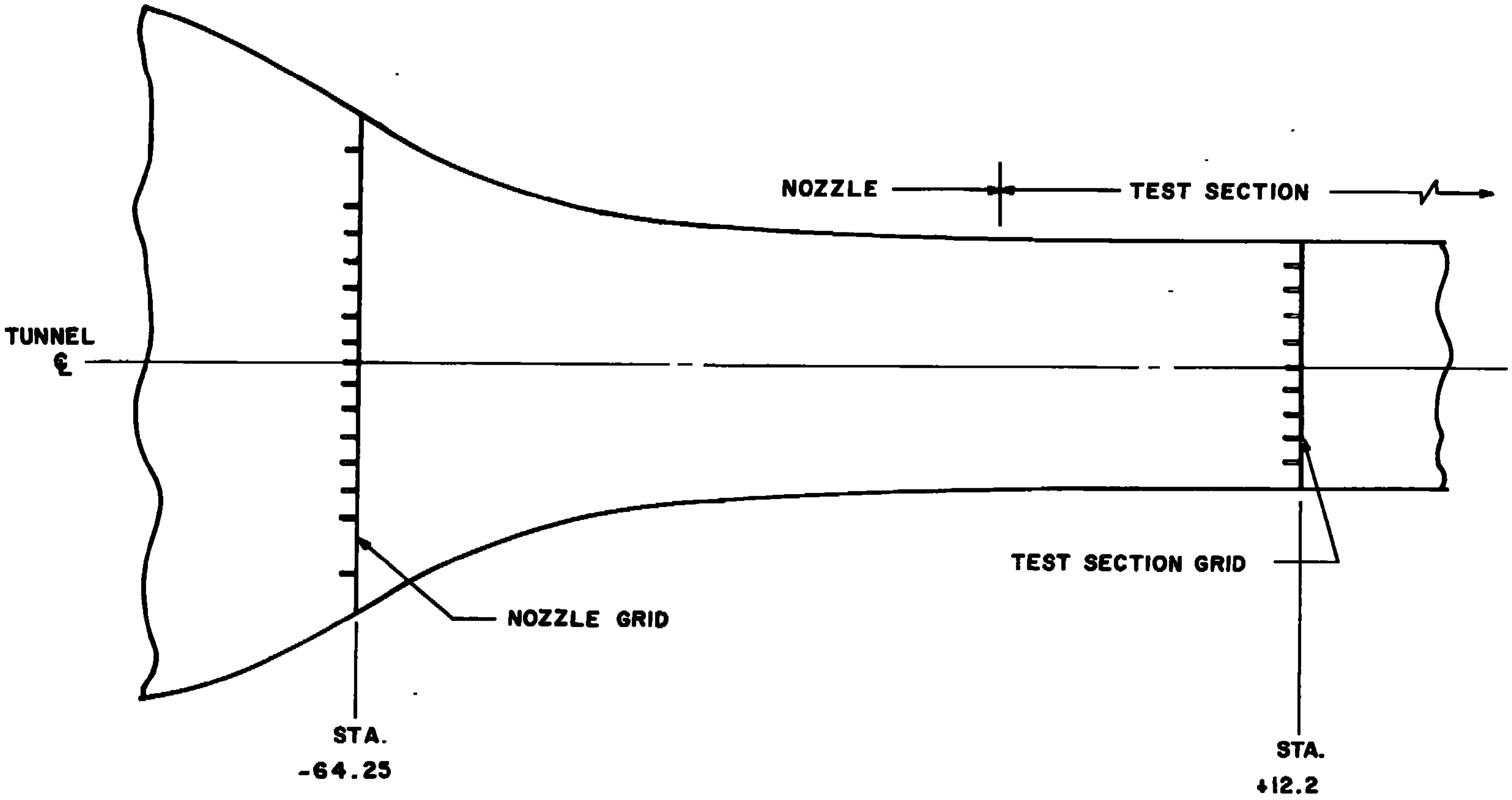


Fig. 4 Location of Thermocouple Grids

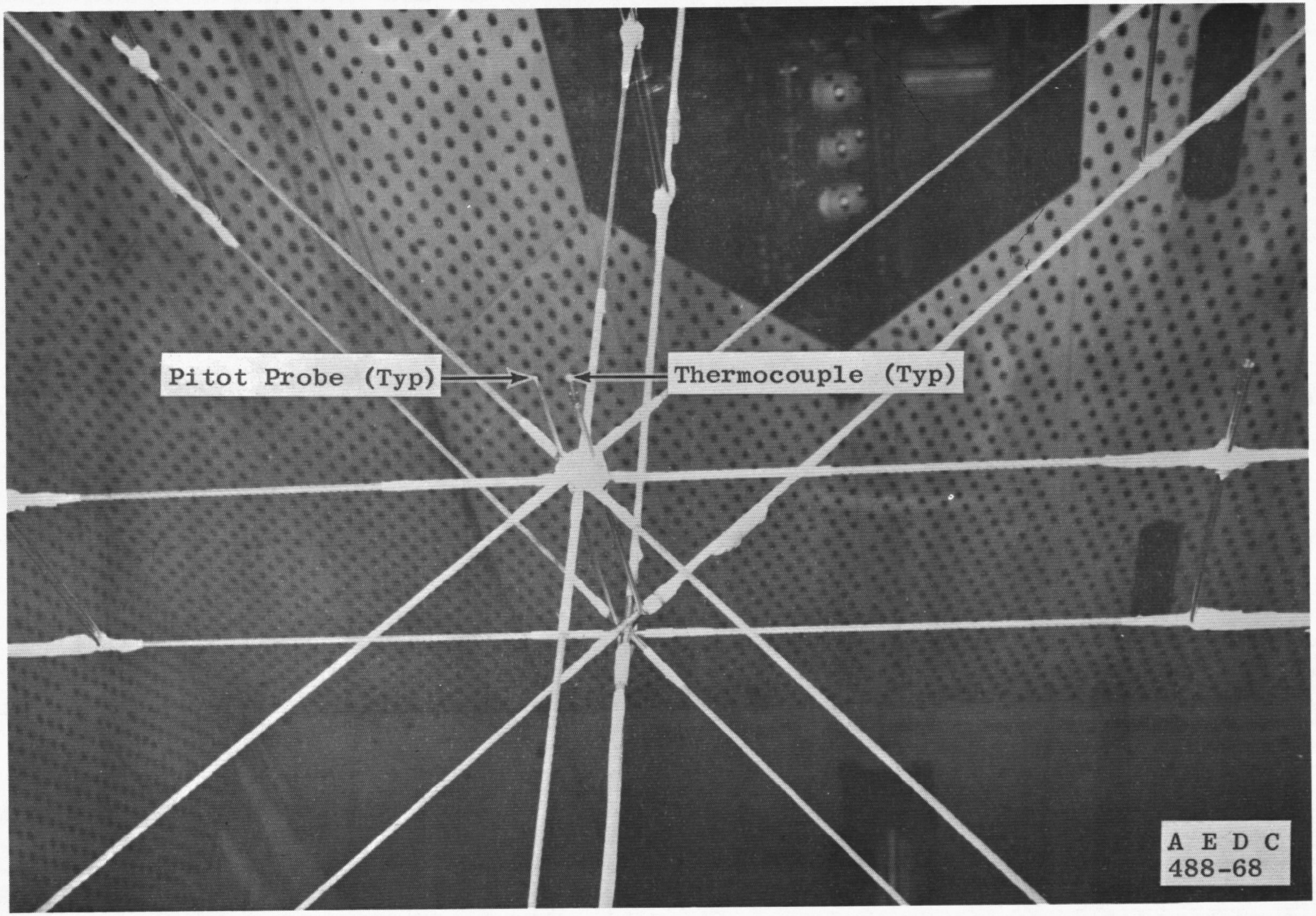
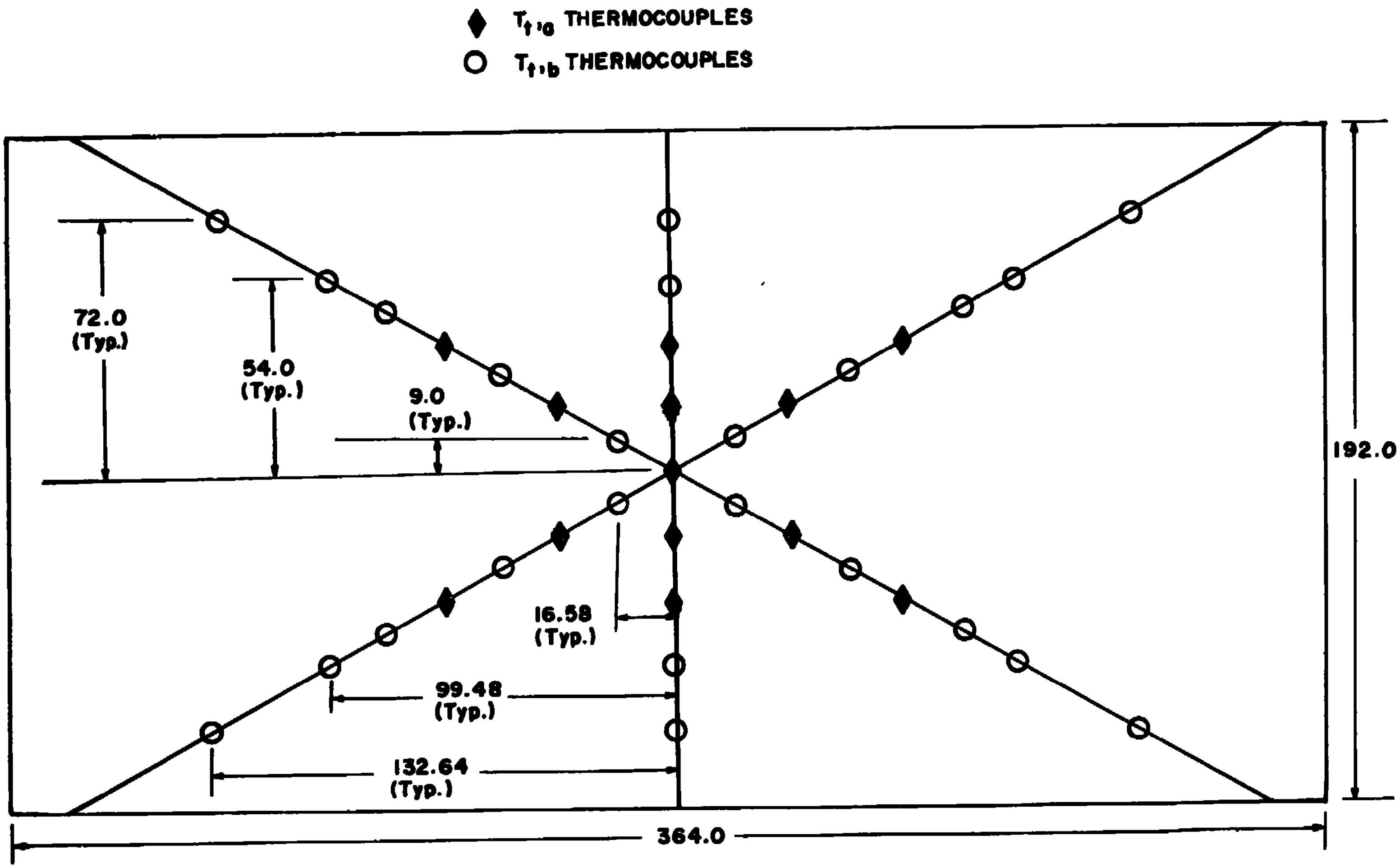


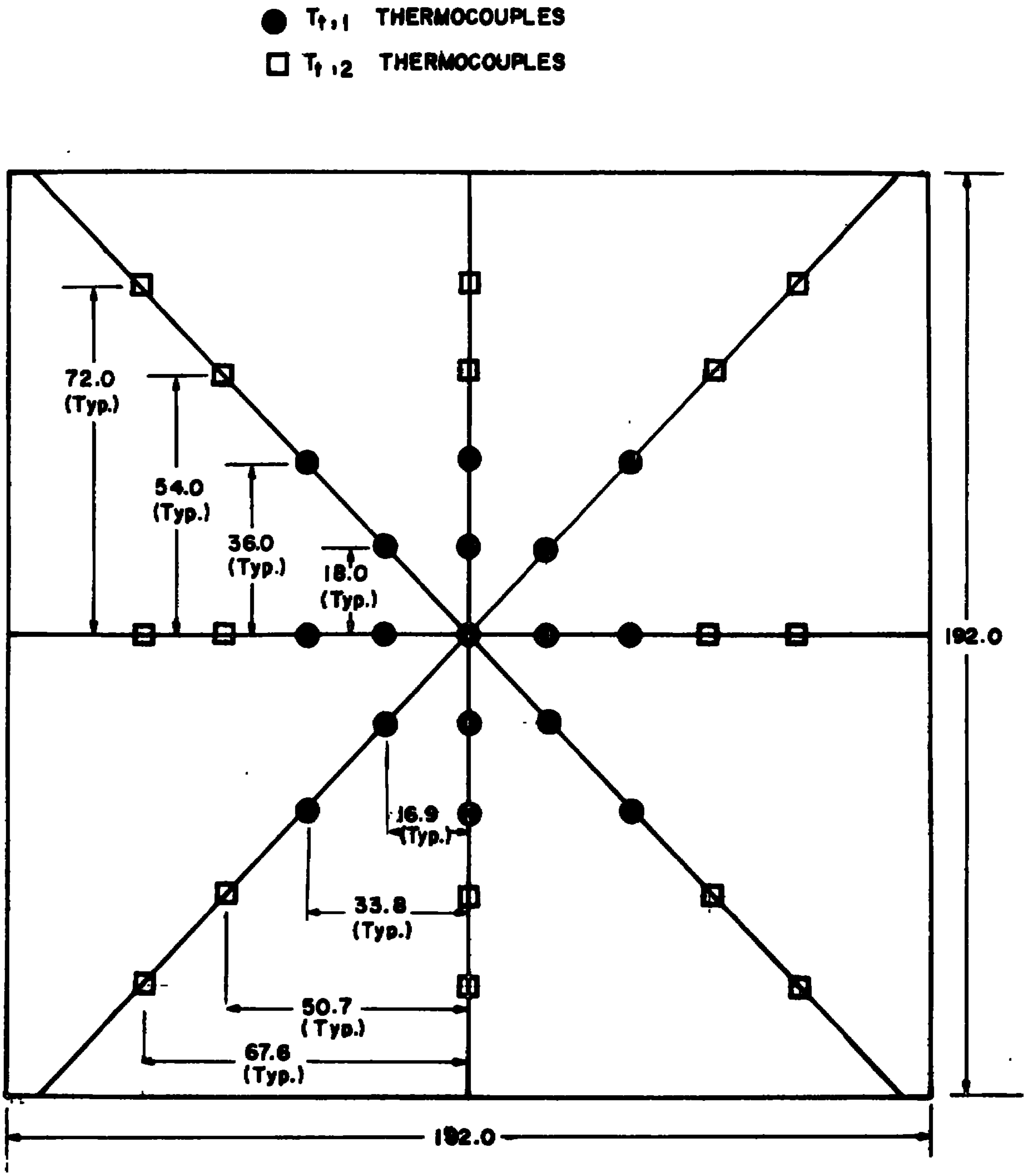
Fig. 5 Total Pressure Probe Installation in Test Section



NOTE: ALL DIMENSIONS IN INCHES

a. Nozzle Contraction Region

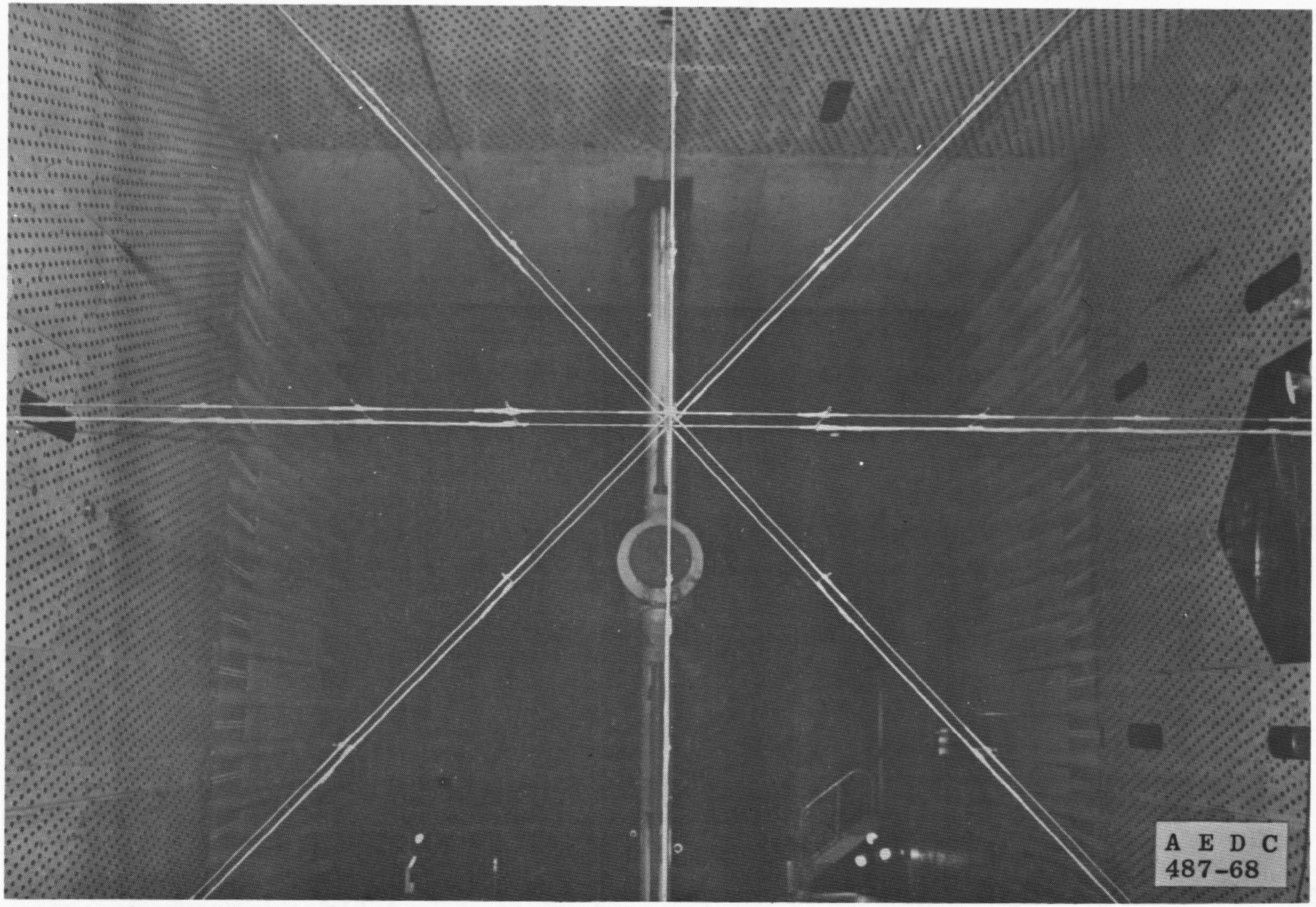
Fig. 6 Thermocouple Grid Schematic



NOTE: ALL DIMENSIONS
IN INCHES

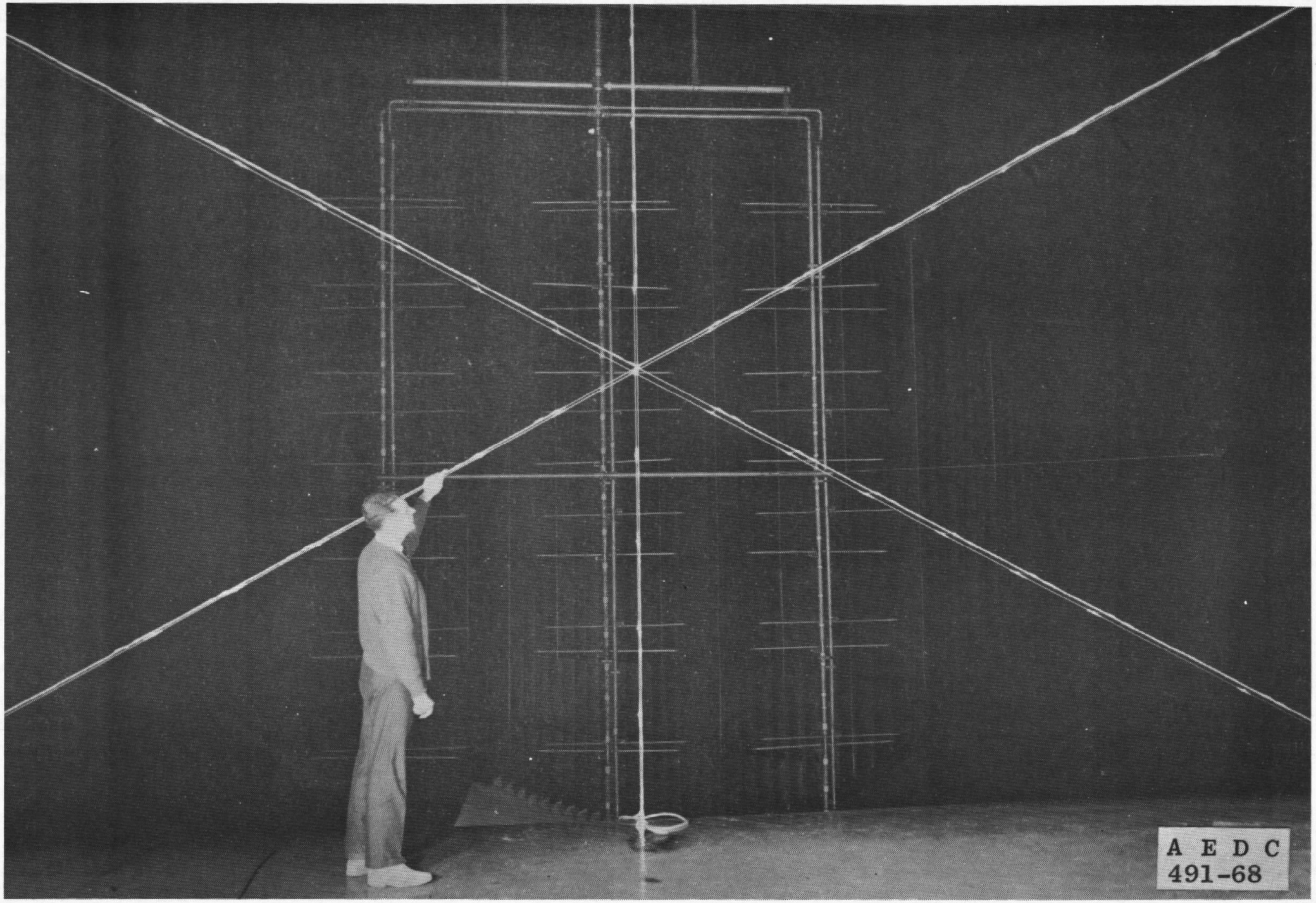
b. Test Section

Fig. 6 Concluded



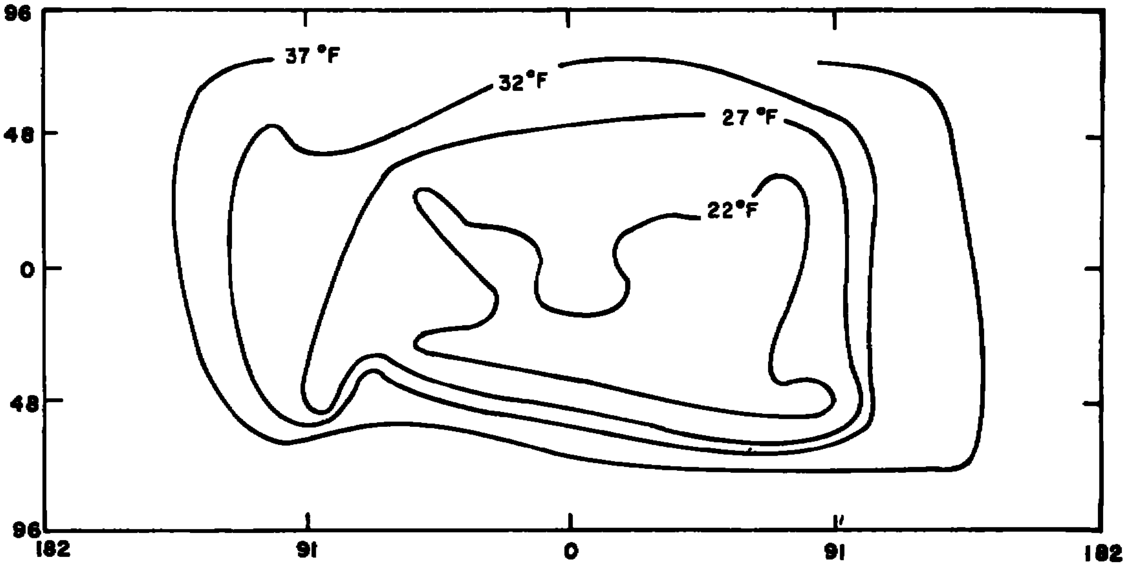
a. View of Test Section Thermocouple Grid Looking Downstream

Fig. 7 Thermocouple Grid Photographs

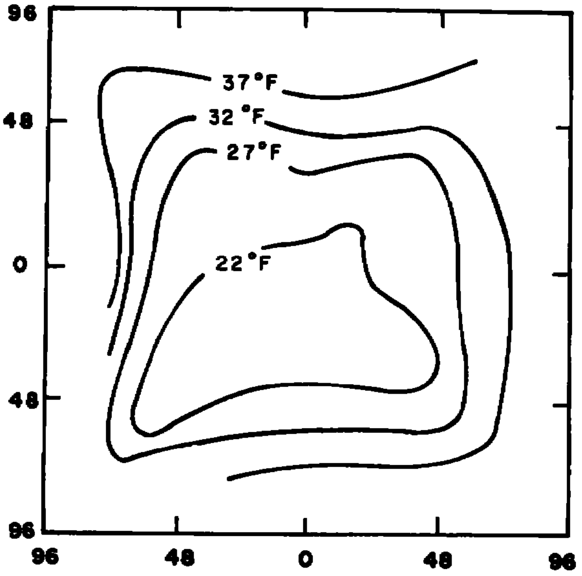


b. View of Nozzle Thermocouple Grid Looking Upstream

Fig. 7 Concluded



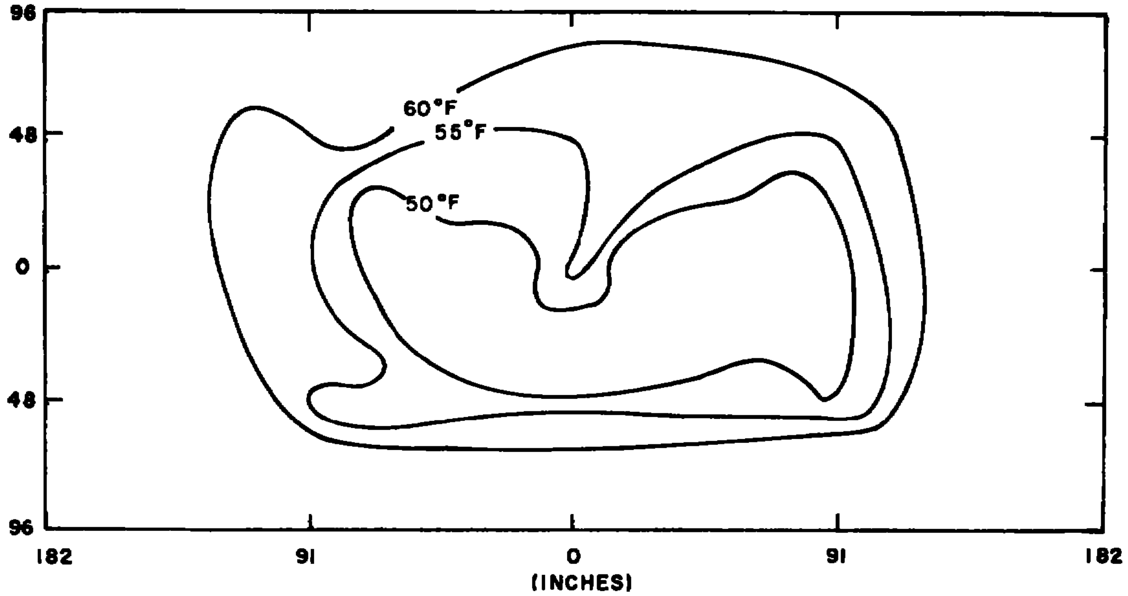
(INCHES)
NOZZLE CONTRACTION REGION



$M = 0.199$
$P_t = 1231.2$ psf
$T_{t,i} = 22$ °F

(INCHES)
TEST SECTION

Fig. 8 Temperature Profiles Looking Downstream



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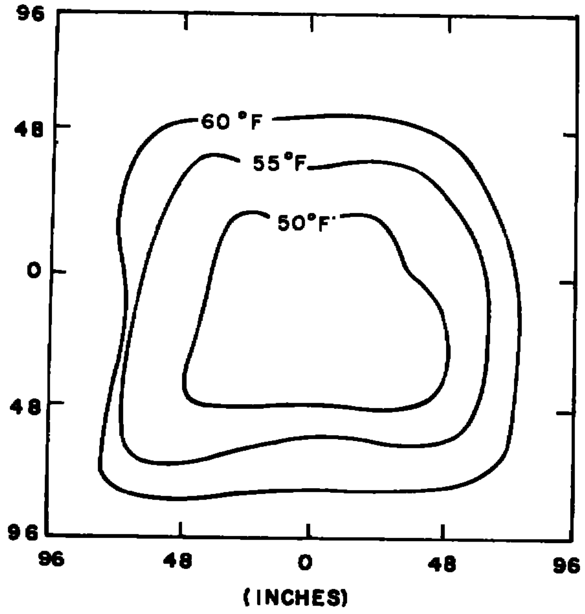
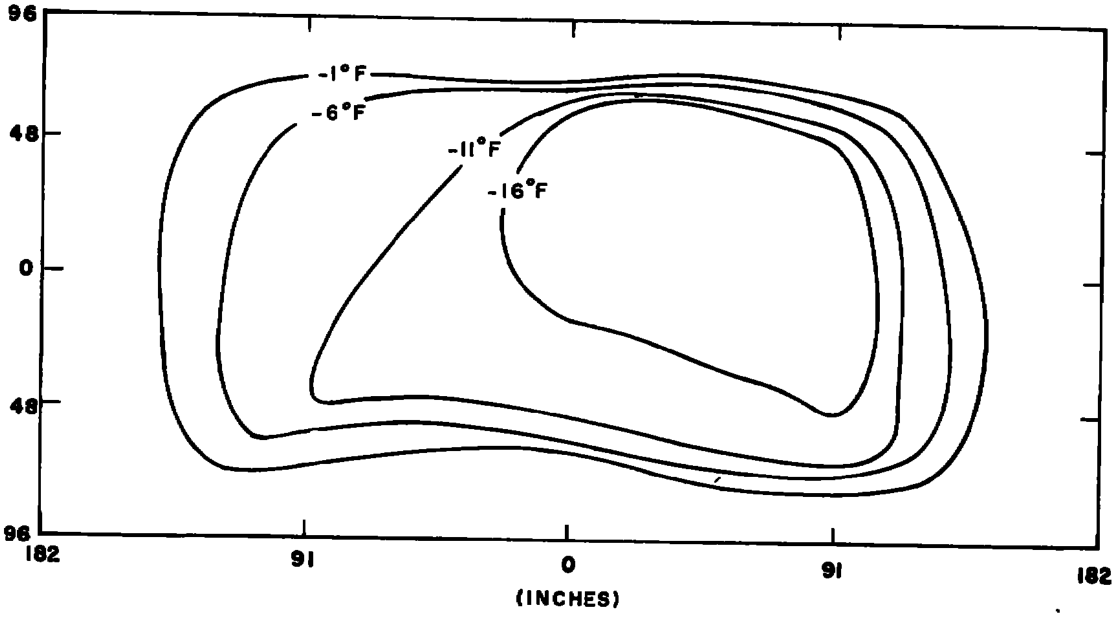


TEST SECTION

M = 0.204
P_t = 599.3 psf
$T_{t,t}$ = 50°F

Fig. 8 Continued



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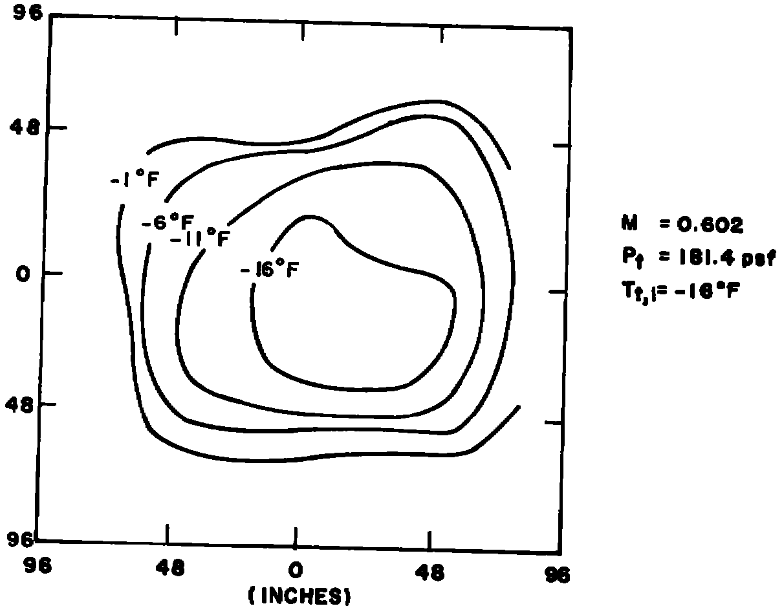
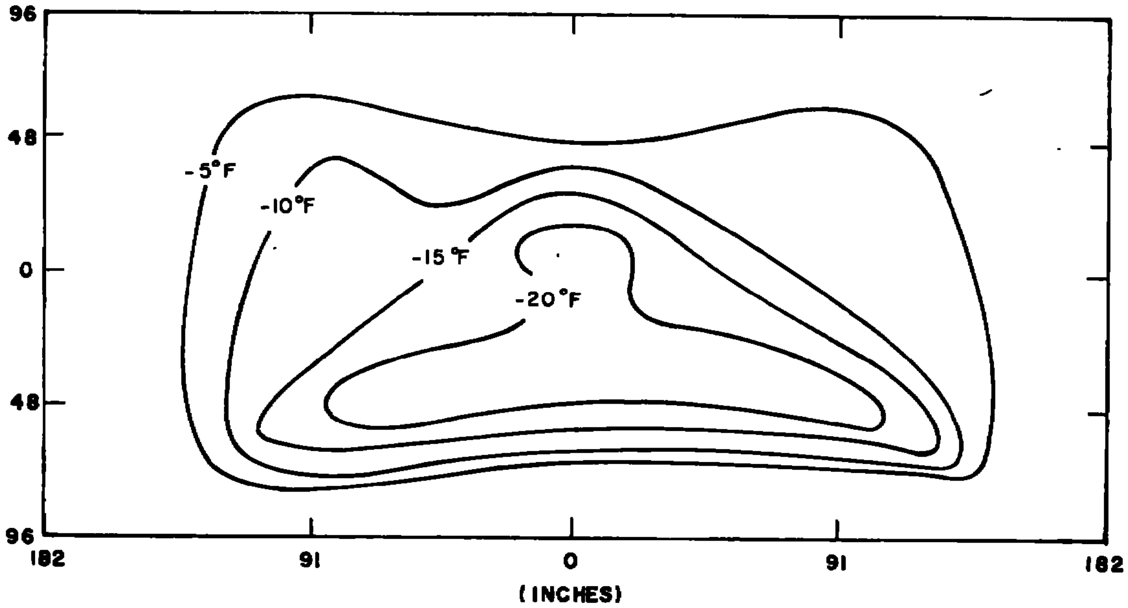


TEST SECTION

Fig. 8 Continued



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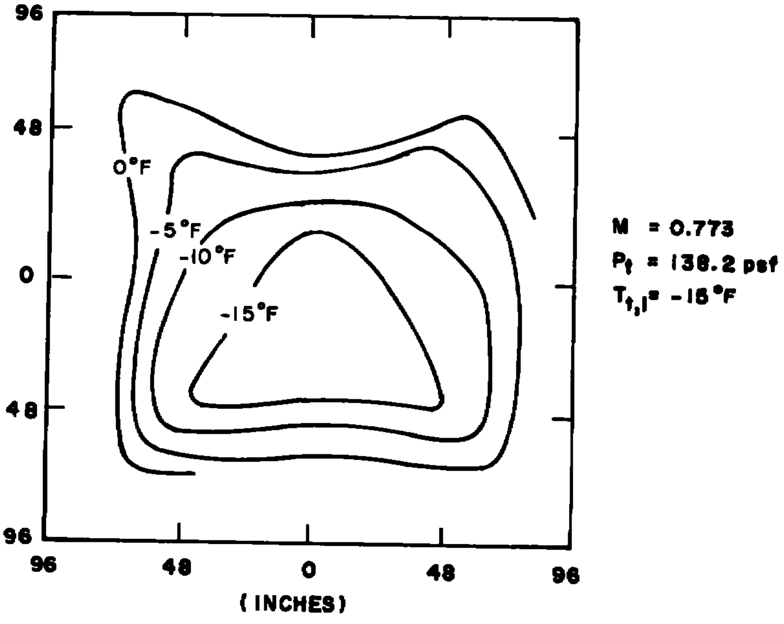
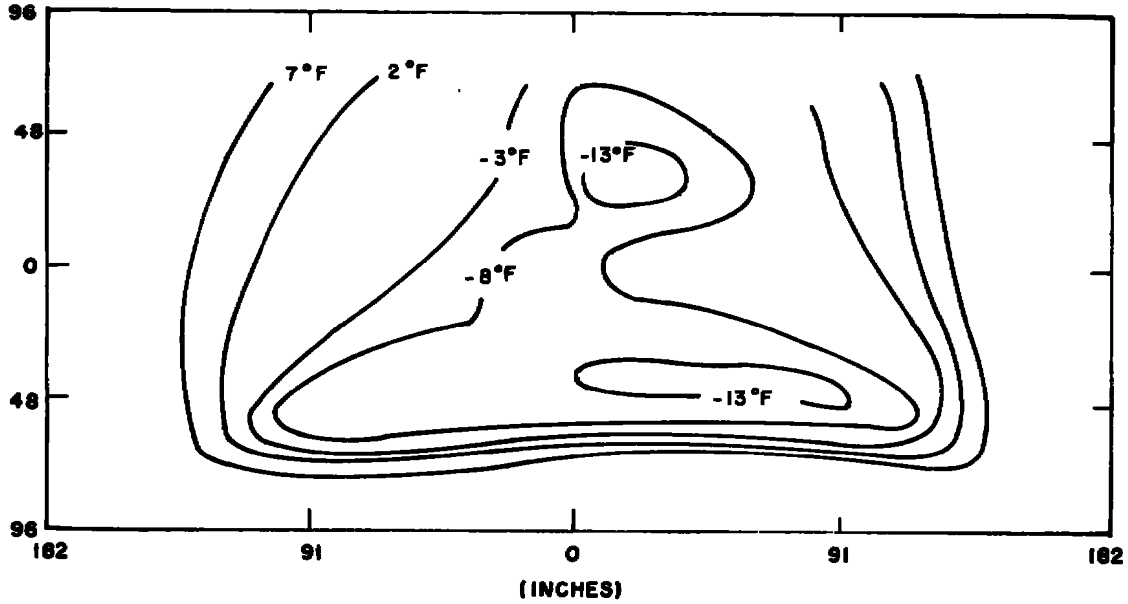


TEST SECTION

Fig. 8 Continued



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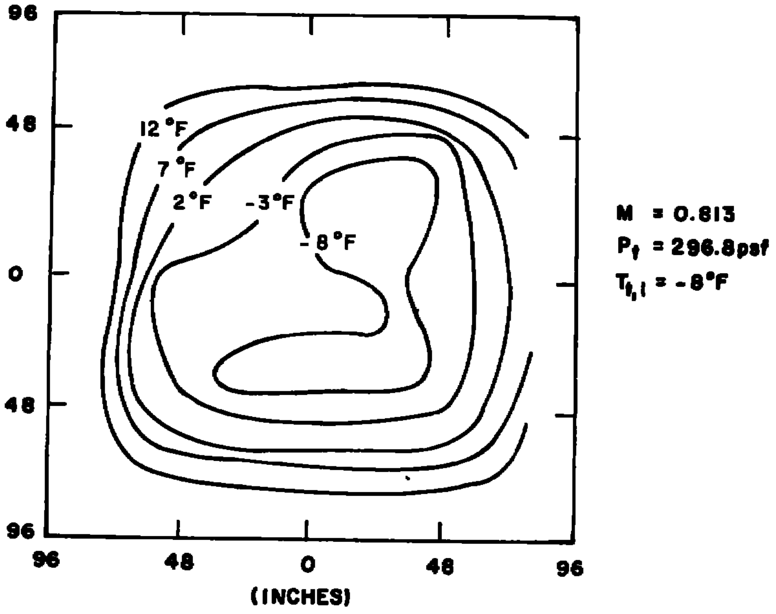

TEST SECTION

Fig. 8 Concluded

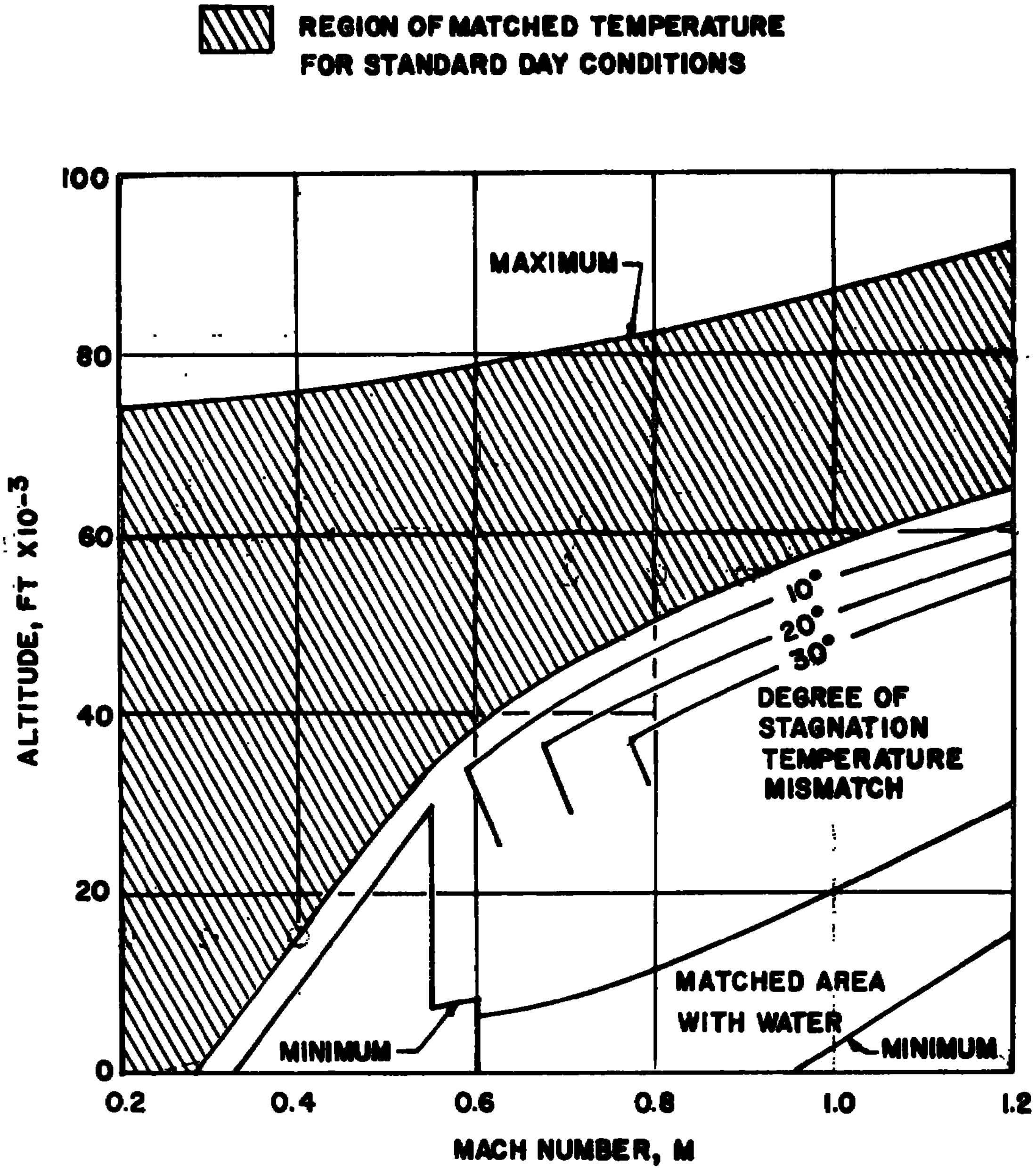

Fig. 9 Operating Range of Tunnel 16T Using Cryogenic Cooling

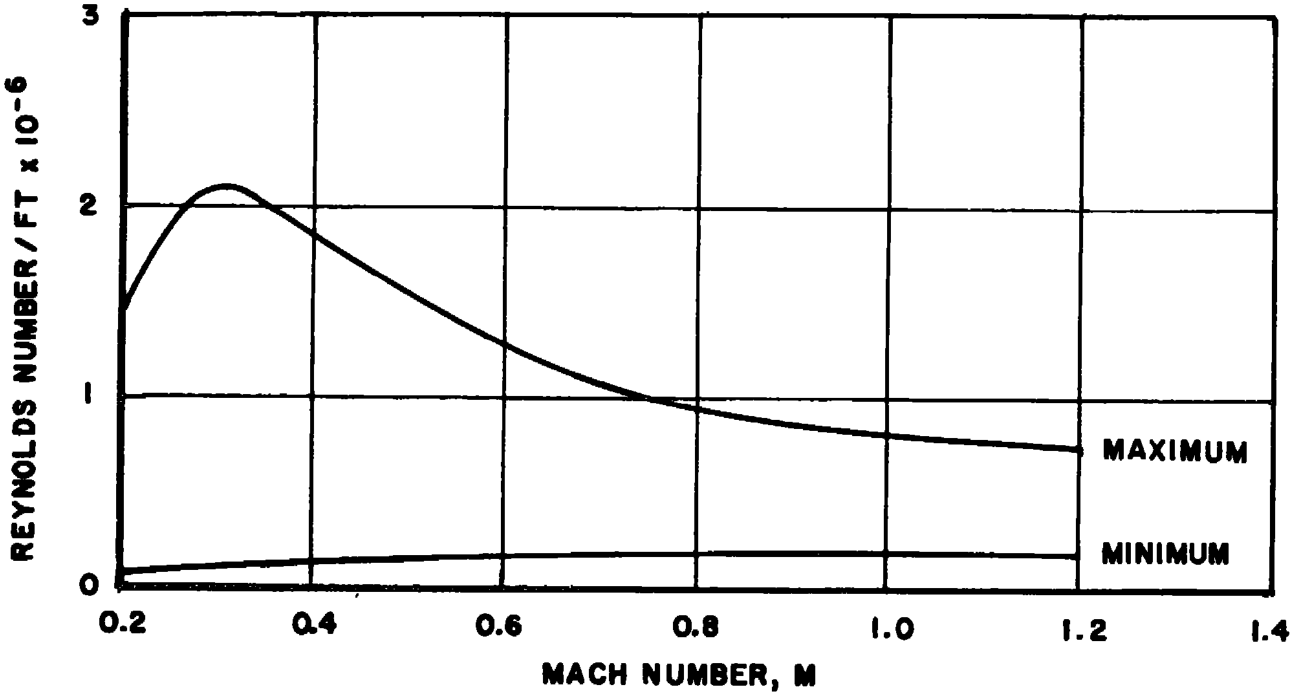

Fig. 10 Tunnel 16T Matched Temperature Reynolds Number Performance

APPENDIX II
THERMOCOUPLE CORRECTIONS

It has been established that corrections should be applied to thermocouple data for Mach number and Reynolds number (Re) effects on thermocouple geometry. Correction factors are discussed at length in Ref. 3 for Chromel®-Alumel® thermocouples. However, since the physical geometry of the subject thermocouples is similar to probe number 6 in Ref. 3, and the corrections are a function of M_∞ and Re and not the type of thermocouple wire used, these corrections can be validly applied to the copper-constantan thermocouples used in this study.

To establish and apply the corrections, define:

$$\Delta = \frac{T_t - T_g}{T_t} \tag{II-1}$$

where T_t = True total temperature, °R

T_g = Measured gas temperature. °R

Δ = Δ (M_∞, Re) recovery factor

Before the corrections can be applied to the thermocouples, a reference recovery-correction factor, Δ_0, must be established. This was provided in Ref. 3 and is shown in Fig. II-1. Having established Δ_0 for the probe, Δ is directly available from Fig. II-2, also extracted from Ref. 3. Solving Eq. (II-1) for T_t yields the true total temperature of the gas as a function of measured gas temperature and recovery factor.

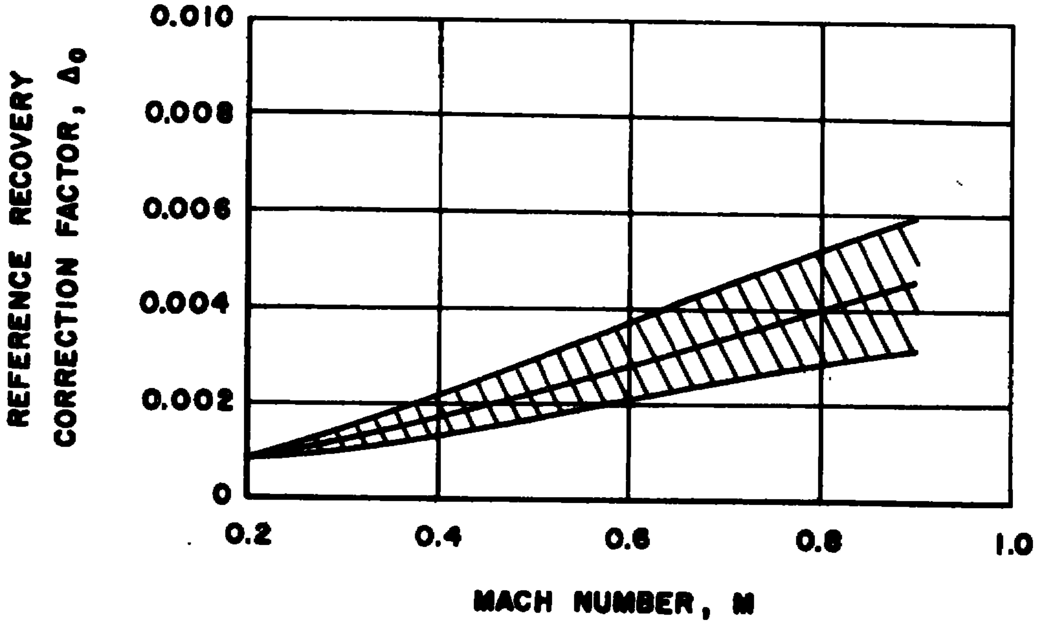

Fig. II-1 Reference Recovery-Correction Factor as a Function of Mach Number

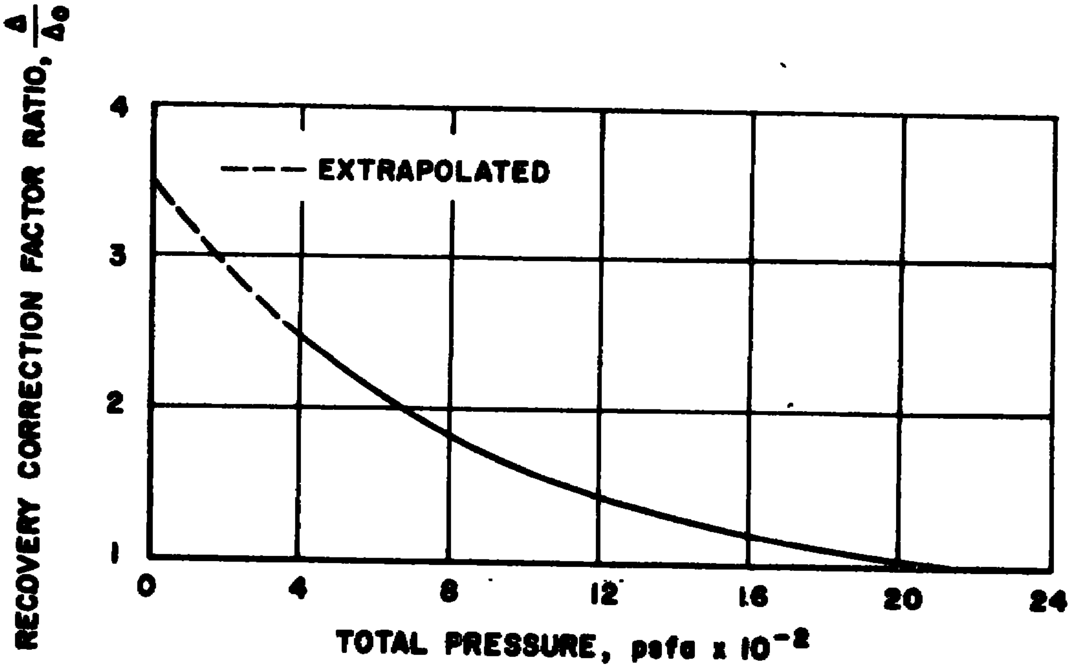

Fig. II-2 Recovery-Correction Factor Ratio versus Total Pressure

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13. ABSTRACT

Tests were conducted in the Propulsion Wind Tunnel, Transonic (16T) of the Propulsion Wind Tunnel Facility at the Arnold Engineering Development Center to determine the test section temperature distribution and calibration relationship to a mean nozzle reference temperature while using a cryogenic cooling system to produce stagnation temperatures from -30 to 30°F. Data were obtained over the Mach number range $0.20 \leq M_\infty \leq 0.55$ for subsynchronous operation and $0.55 \leq M_\infty \leq 1.2$ for synchronous operation. The temperature deviation in a 6- by 6-ft core was found to be less than ±8°F in the stagnation temperature range $-30^\circ F \leq T_t \leq 30^\circ F$. It was also determined that an offset calibration factor of -2°F must be applied to the mean nozzle reference temperature to obtain the average test section temperature in a 6- by 6-ft core.

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cryogenics						

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