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THE DEVELOPMENT OF A SMALL MACH 10 HYPERSONIC WIND TUNNEL,

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The advice of Prof. S. M. Bogdonoff during the entire program is greatly appreciated.

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ABSTRACT

A hypersonic wind tunnel was ~~has been~~ constructed at the Gas Dynamics Laboratory using air as the working fluid. This tunnel, capable of operating from Mach 5 to 10 at Reynolds numbers per inch of 0.03 to 0.40 million, has a test section diameter of 3½ inches. The key part of the installation is a storage heater which consists of a coil of heavy-walled inconel pipe which is preheated electrically to the desired stagnation temperature. A maximum temperature of 27000°R. at a pressure of 1500 psia is generated for running times of 6 to 12 minutes.

Preliminary calibration tests using conical nozzles at M = 7 and 10 have verified the basic design and operating range.

SYMBOLS

A	constant in Clausius-Clapeyron equation
B	constant in Clausius-Clapeyron equation
M	Mach number
p	pressure
Re	Reynolds number
T	temperature

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I. INTRODUCTION

The Gas Dynamics Laboratory has been operating a series of supersonic blowdown wind tunnels for over a decade. These wind tunnels were not supplied with heaters and therefore were limited to a Mach number of about 4 (Refs. 1 and 2). Hypersonic tunnels using helium as the test gas have also been in use for this period of time operating at Mach numbers from 7 to 24 (Refs. 3 and 4). There are presently several other hypersonic facilities using helium, but few comparisons have been made in air tunnels at identical conditions to study the effects of testing in different gases (Ref. 5). The present tunnel has been designed to give free stream Reynolds numbers similar to those obtained by the helium tunnels at the Laboratory in the range of Mach number from 7 to 10. The basic design was dictated by a desire to keep the installation as simple and trouble-free as possible and to maximize the utility of the basic high pressure and vacuum systems available in the Laboratory. The unique feature of the tunnel to be discussed is the coil type storage heater and the main emphasis will be placed on its design and performance. The original idea of the heater was conceived by Dr. Andrew G. Hammitt (now with the Space Technology Laboratories).

II. TUNNEL DESIGN

A. General Considerations

Before design of the new hypersonic air tunnel was begun, certain basic facilities existed in the Laboratory. A high pressure air supply was available, consisting of four reciprocating compressors, a dryer and 3000 psi air storage bottles. Also available was an air ejector system capable of providing a back pressure down to 0.8 inches of mercury absolute.

Considering the capabilities of the air supply system and the ejector, and the desire to duplicate part of the range of the helium tunnels, the following design parameters were set: Test section size of approximately 3 inches, Mach number range from 7 to 10, maximum stagnation pressure of 1500 psia, maximum stagnation temperature of 1500°F., and run times of up to 10 minutes. The maximum temperature was determined from air condensation considerations noted in the next section. The relatively long run times were desired in order to use the same standard type instrumentation used in the other supersonic and hypersonic tunnels of the Laboratory and to permit detailed studies of flow fields and boundary layers. To obtain the desired Mach number and stagnation pressure range, a heater is required to prevent condensation of the air at the test section conditions. Experimental data for condensation conditions of nitrogen, oxygen and mixtures of both are available from several sources (Refs. 6 to 17). It is possible to match these data fairly closely by the Clausius-Clapeyron equation

$$\log_{10} p = -\frac{A}{T} + B$$

where p is the condensation pressure in atmospheres
T is the condensation pressure in degrees Rankine

and A and B are experimentally-determined constants.

Over most of the practical range of hypersonic wind tunnel pressures, experimental data indicate $A = 648$ and $B = 445$. The stagnation pressure and temperature can readily be calculated from the isentropic flow relations and the test section condition. For air ($\gamma = 1.4$) the required stagnation temperature to just avoid condensation in the test section is given in terms of the stagnation pressure and Mach number by

$$\frac{A}{T_o} \quad 1+\frac{M^2}{5} \quad = B + 3.5 \log_{10} \quad 1+\frac{M^2}{5} \quad - \log_{10} p_o$$

and the curves of Figure 1.

Using the limitations of the installed pressure and vacuum systems, the operational characteristics of the vacuum system with mass flow and the variation as stagnation temperature requirements with pressure and Mach number, the operational conditions of the facility could be calculated. In terms of free stream test section Reynolds number per inch and test section Mach number, the performance is shown in Figure 2.

B. Components

The tunnel was designed to allow for maximum flexibility with minimum "special" items. A layout of the facility is shown in Figure 3. The heater and settling chamber are essentially fixed.

Components of the tunnel downstream of the settling chamber are mounted on carts which roll on tracks. A telescoping duct sealed with a flexible rubber "boot" at the diffusor end of the tunnel allows movement along the tracks for a distance up to 12 inches to permit model installation and modified test and survey sections. A photograph of the layout is shown in Figure 4.

The design of the heater is the key component of the tunnel. The condensation limits of Figure 1 indicated that a temperature of about 1500°F. was required to operate at $M = 10$ and $p_o \sim 1500$ psia. This results in a set of heater specifications which, although not beyond common practice, usually requires some considerable complication. The use of storage type heaters consisting of a pressure tank and a large mass of material, or continuous electrical heaters (both fully able to cope with the required specifications) are neither cheap nor simple. The electrical power required for direct electrical heating was not available. The solution chosen was to use a storage type heater, but to eliminate the cost and complication of the hot high pressure tank by using both for heat storage and pressure containment.

The characteristics of Inconel are quite satisfactory for the desired application. It is available in pipe form, is relatively inexpensive, and retains its strength and resists oxidation at temperatures over 1600°F. Its ultimate strength versus temperature for various times of exposure is given in Figure 5.

The total length of pipe in the coil was based on two considerations: the heat transfer length and the heat storage capacity. If the pipe is initially at the desired stagnation temperature, a cold slug of air will have to travel a certain length before its temperature is nearly that of the pipe. This "heat transfer length" can be calculated from the following relationship:

$$L = \frac{mC_p}{D\pi h} \ln \frac{T_w - T_i}{T_w - T_g}$$

where	m	the mass flow rate of the air
	C_p	the specific heat of the air
	h	heat transfer coefficient
	D	inside diameter of the pipe
	T_w	wall temperature of the pipe
	T_i	initial temperature of the air
	T_g	final temperature of the air

This relationship is derived by setting up a heat balance for a differential element of length and then integrating assuming T_w, h and C_p are constant.

The heat transfer coefficient, h, was calculated from the relationship:

$$h = 0.023\left(\frac{DG}{\mu}\right)^{0.8}\left(\frac{C_p\mu}{k}\right)^{0.4}\frac{k}{d}$$

where	G	the weight velocity of air per unit area
	μ	viscosity of the air
	k	thermal conductivity of the air

The air properties were evaluated at some bulk average temperature.

The "heat storage length" is found by first determining the quantity of heat required to heat the air from initial to final temperature and then calculating the mass of pipe, consequently the length required to hold this heat. The total length of pipe required is then the sum of the "heat transfer length" and "heat storage length". The values calculated were 40 feet for the former and 110 feet for the latter using 3/4 inch double extra heavy Inconel tubing. The heater coil was therefore made from 150 feet of tubing wound as a 2 foot diameter helical coil. Spacers constructed of aluminum oxide were inserted between the coils to prevent contact with each other. The coil was placed in a steel enclosure lined with insulating firebrick. A photograph of the heater in its lined box is shown in Figure 6.

The pipe is heated electrically prior to the run. A three-phase circuit is used to permit both ends of the coil to be grounded as well as to balance the live loads. The coil is wired as a delta load with one end grounded (Figure 7). The power is supplied by a three-phase 19.5 kva transformer having a 440 volt primary and four secondary taps varying from 15.0 to 18.5 volts.

From room temperature, the coil heats to 1000°F. in approximation 1¼ hours and to 1500°F. in about 2½ hours. After a test, the heater takes about 1-1½ hours to reheat to 1500° for a subsequent test.

The power to the heater is controlled by a Brown Pyrovane. The device has an adjustable neutral zone and a fail-safe mechanism to prevent burn-out in case of thermocouple failure. When the heater reaches the desired temperature, the controller maintains this temperature to within 10°F.

The heater gives a 5 to 12 minute run time (depending on the mass flow rate). The power is left on during a run, providing a slight increase in run times over the purely "storage" operation. A typical stagnation temperature versus time plot is shown in Figure 8 for the Mach 9.6 nozzle at a stagnation pressure of 750 psia. About 3 minutes is required to heat the settling chamber and nozzle after which approximately 8 to 9 minutes of testing time is available. This testing period can be shifted to within a fraction of a minute of the starting time by a longer "preheating" period during which a small flow of hot air is allowed to pass through the settling chamber.

The air to the tunnel is regulated by a Moore Nullamatic controller, Moore diaphragm type pneumatic positioner and Hammel-Dahl valve. Once the stagnation pressure is adjusted, it is automatically held to within 10 psi despite considerable supply pressure variation. The air to the ejector is regulated by means of a Conoflow valve with a diaphragm type pneumatic actuator.

The settling chamber was welded directly to the heating coil and acts as one of the electrical terminals (Figure 9). The chamber was machined from inconel bar stock. No screens or filters are used in the chamber, which has an inside diameter of 1 inch. The velocity of air in the settling chamber varies from 22 fps using the Mach 10 throat to 100 fps using the Mach 7 throat. The stagnation temperature is measured by a chromel-alumel thermocouple mounted through the sidewall. The seal between the chamber and nozzle is provided by an inconel pressure ring between two inconel flanges. This ring provides an effective seal which withstands both the high pressures and temperatures of operation.

A simple conical nozzle was used for the first tests. The initial section of the nozzle was made of inconel and was replaceable. Two similar sections of different throat size provided test section Mach numbers of 7 and 9.6. Because of the low heat transfer rates once the flow has expanded to low pressures, the downstream section of the nozzle could be made of brass. Although the entire settling chamber and nozzle needed no cooling (the critical sections were made of the same material as the heater tubing, inconel), thermal stabilization of the nozzle was required to obtain constant Mach number with time and so the entire nozzle section was wrapped with copper coils carrying cooling water.

The nozzle had a 6° half expansion angle with an exit diameter of $3\frac{1}{4}$ inches (Figure 10). This was followed by a constant area section in which recessed quartz windows were mounted.

The test section was followed by a constant area section which held the drive mechanisms for surveying the tunnel. A fixed diverging diffusor expanded from the traverse section to the cooler (17"x17") with a total included angle of 12°. The cooler was required to decrease the volume flow into the following ejector system and was made of 8 banks of aluminum finned tubes. The water flow to the cooler was about 10 gallons per minute. The pressure drop across the cooler was approximately 0.03 inches mercury for a mass flow rate of 0.12 pounds per second of primary air flow. An air ejector which was originally designed for the helium hypersonic wind tunnel (Ref. 18) was used to reduce the back pressure. The minimum suction pressure with the ejector was 0.8 inches mercury absolute (Figure 11).

Certain safety measures must be employed because of the high temperatures and pressures of operation. A Brown "Pressuretrol" was used which acts to automatically shut off the tunnel air supply when the stagnation pressure drops below a set value. Ordinarily, If a break occurred, the stagnation pressure would drop and the automatic controller would open the pneumatic valve wider to raise the pressure. If the pressure falls below a certain value, however, the Pressuretrol acts to close a solenoid valve which would in turn close the pneumatic valve. A spring-loaded overriding switch was provided for starting the tunnel. In addition to the Pressuretrol, a constriction is placed before the heater to limit the mass flow in case of a break in the pipe or faulty operation of the pneumatic valve. The lid of the heater, which consists of firebrick fastened to a steel plate, is constrained by a steel rod to lift only 1 inch and to direct escaping air upwards and away from the tunnel operator in case of a break in the heater pipe. Since the strength of the Inconel heater pipe decreases with cycling at high temperatures, it is planned to replace the pipe at considerably under its projected lifetime, as based on a steady high temperature.

III. PRELIMINARY MEASUREMENTS

A tunnel calibration was made for each of the nozzles at various stagnation conditions of pressure and temperature. Some typical results of these surveys are presented. A cross tunnel Mach number survey made with a 5-tube pitot rake is shown in Figure 12 for the Mach 9.6 nozzle. The cross tunnel Mach number variation is less than ± 0.1. The centerline Mach number distribution for the Mach 9.6 nozzle is shown in Figure 13 with the Mach number obtained from both the wall static pressure measurements and the centerline pitot pressure measurements. The Mach numbers obtained by both methods are in good agreement with each other. The Mach number gradient is 0.2 per inch. A total temperature measurement was made across the tunnel (Figure 14) using a single shielded probe with a vent area one-quarter the inlet area. For the Mach 9.6 nozzle, the measured value of the total temperature was about 95% of the measured stagnation value, excellent agreement for the type of probe used.

Although the density in the test section is quite low and the recessed windows may not be optimum, there was no difficulty in obtaining reasonable schlieren photographs of shocks and boundary layers on a 10° wedge of 2 inch span at $M = 9.6$ (Figure 15). A simple skewed two mirror system (8 inch diameter, 80 inch focal length) was used with a 1 microsecond spark light source. No difficulty was experienced with the quartz windows during the duration of the tests but one window did break after the test was completed. It is believed that this was due to thermal stresses caused by uneven cooling.

IV. CONCLUDING REMARKS

A small blowdown hypersonic wind tunnel has been constructed to operate at Mach numbers up to 10. The air is heated by passing it through a coil storage heater consisting of 150 feet of Inconel pipe which is heated electrically. The heater operated satisfactorily at maximum conditions of 1500 psia and 1500°F. Run times of 10 minutes duration are possible every 2 to 3 hours. For the first tests, a simple conical nozzle was used to give Mach numbers of 7 and 10 in the test section of 3½ inches diameter. Total temperature and pitot pressure surveys and static pressure measurements along the wall indicated good condensation free flow and a standard two-mirror schlieren system showed that flow visualization is not a severe problem.

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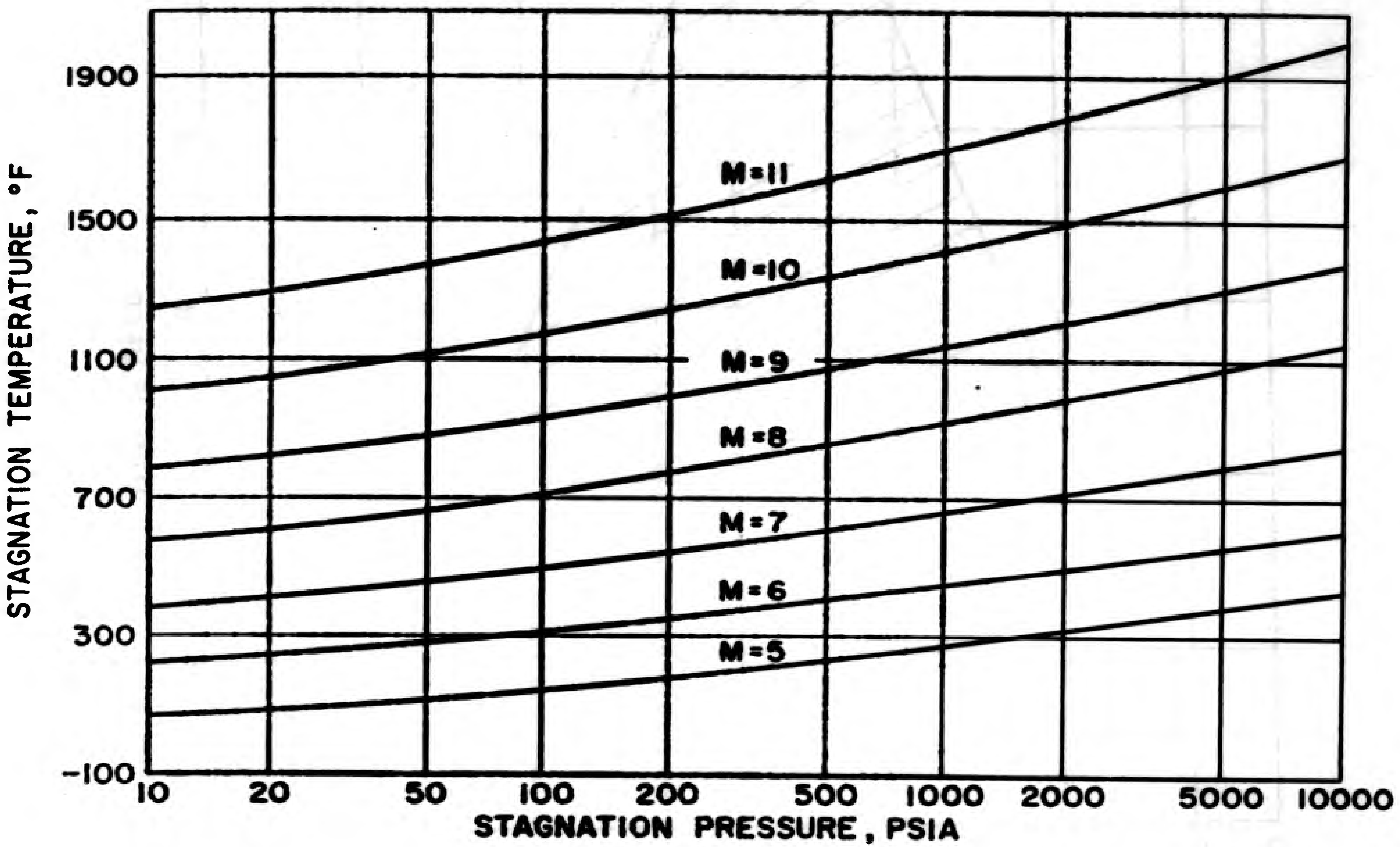

Figure 1. Equilibrium condensation curves for air

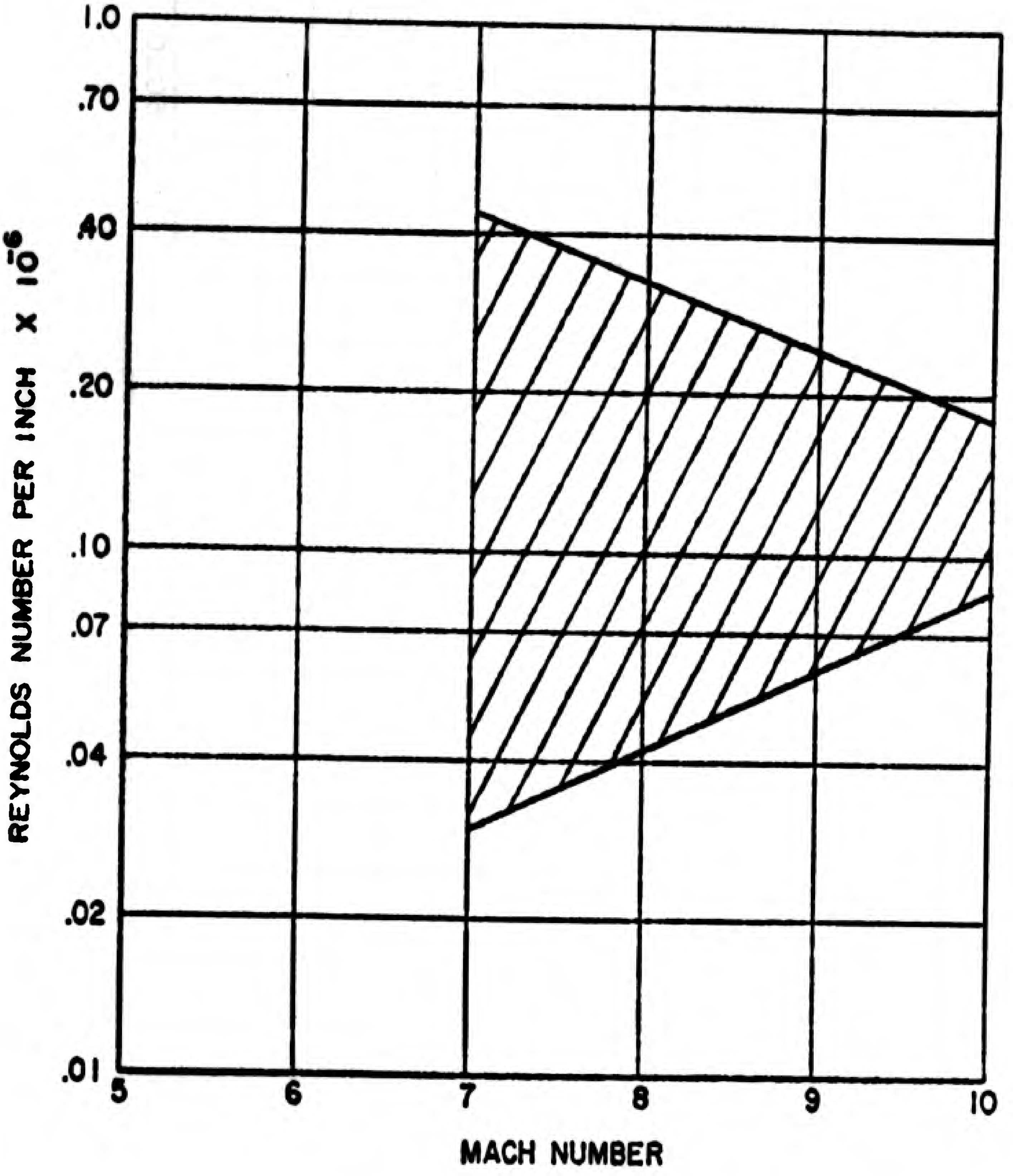

Figure 2. The Reynolds number-Mach number map

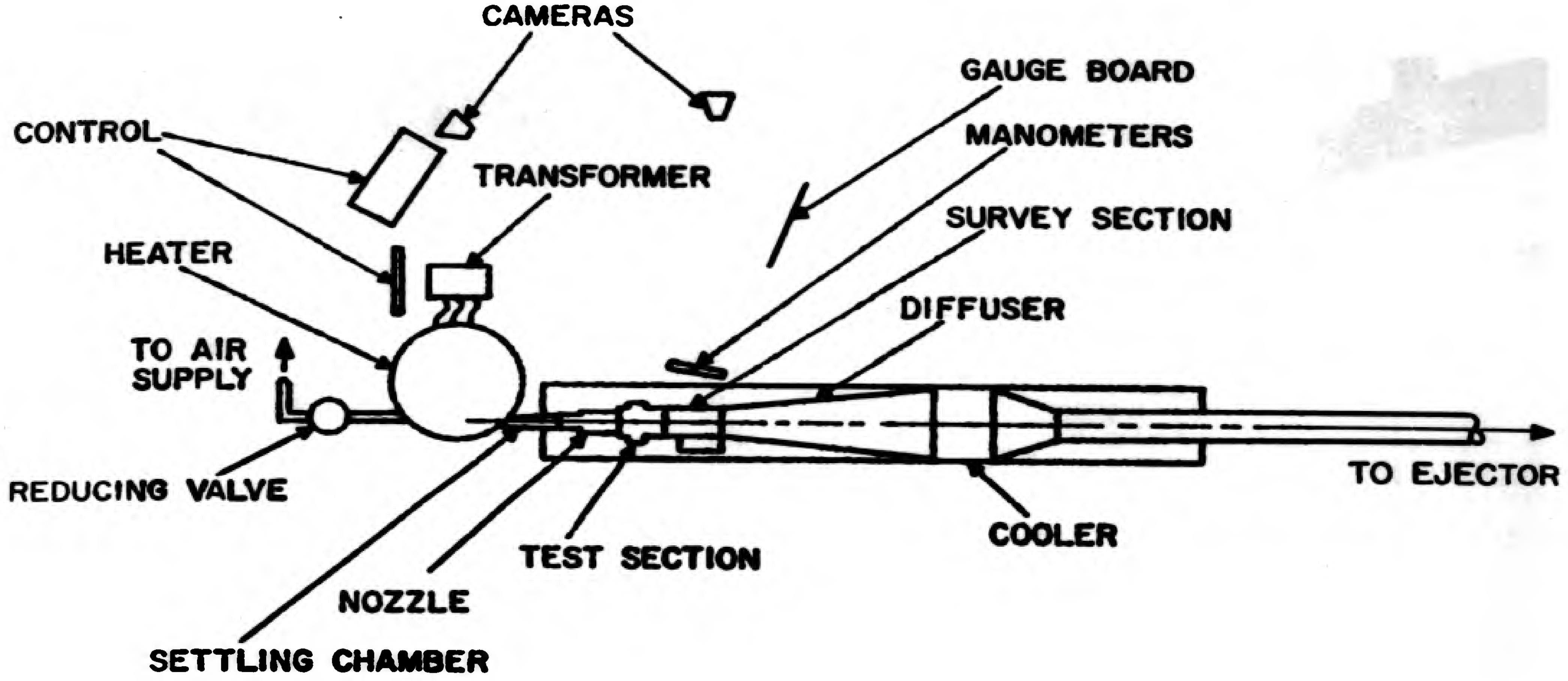

Figure 3. Tunnel layout

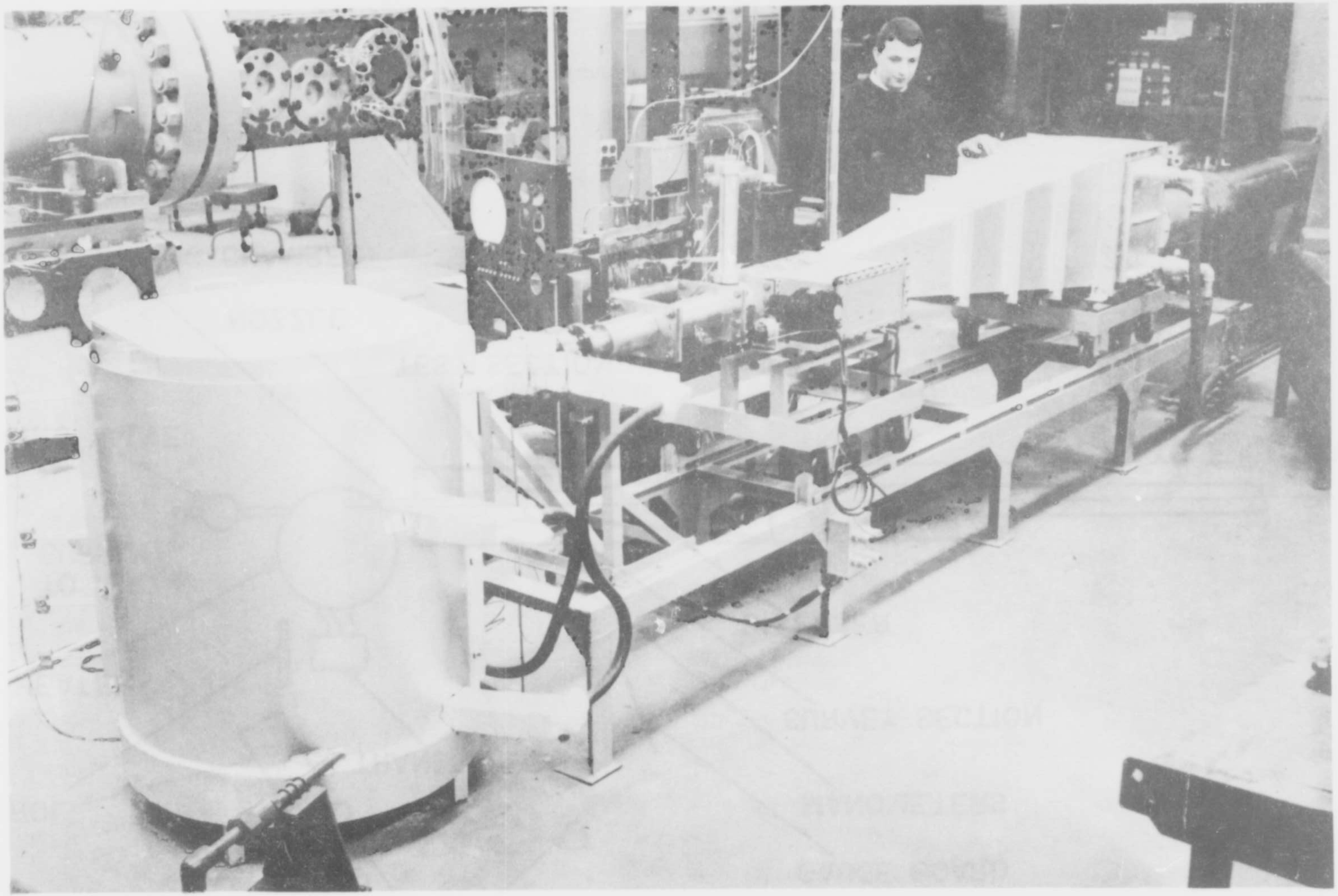

Figure 4. General view of the hypersonic M ~ 10 air tunnel

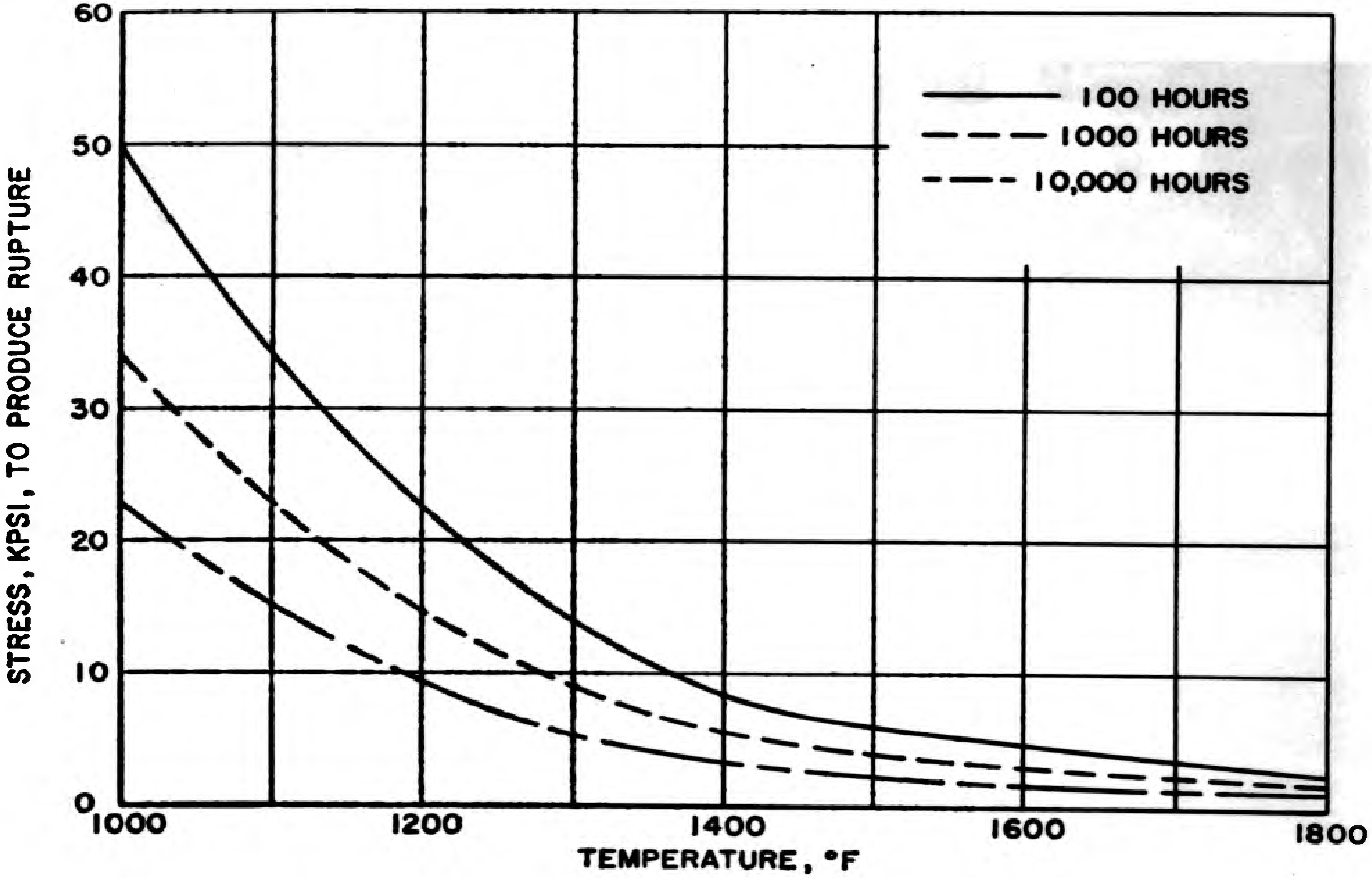

Figure 5. Rupture strength of inconel at elevated temperatures

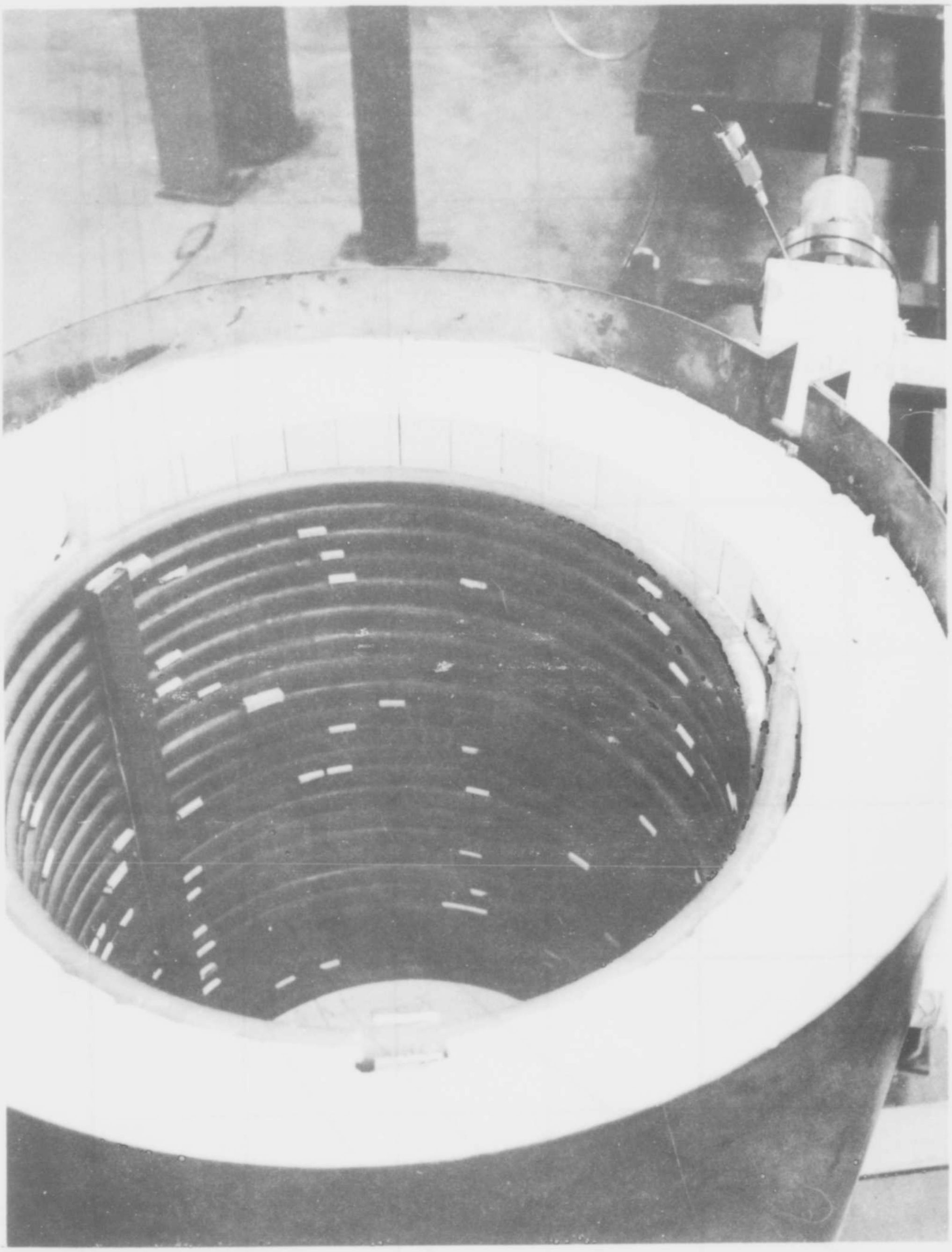

Figure 6. Inconel coil in housing with cover removed

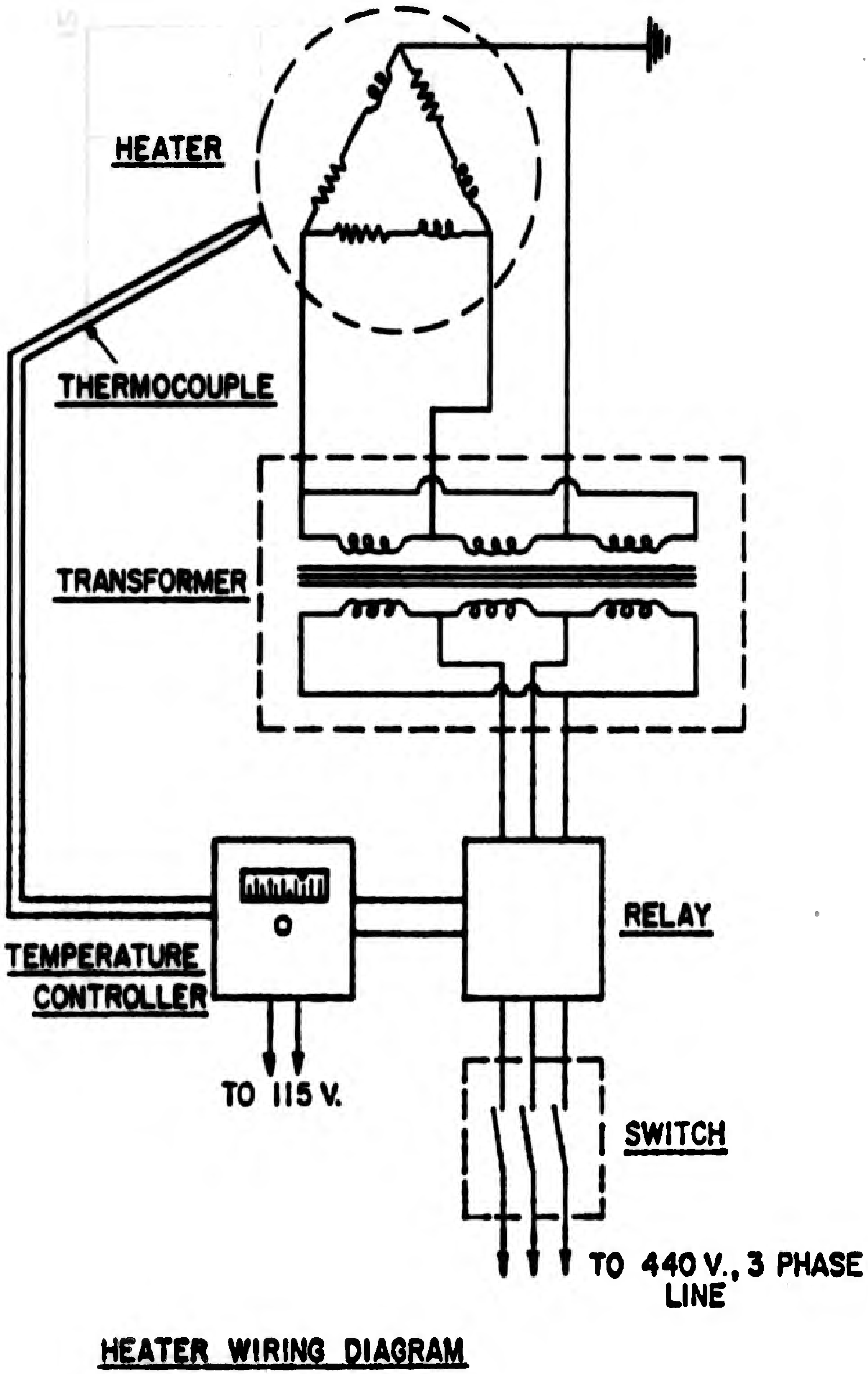

Figure 7. Heater wiring diagram

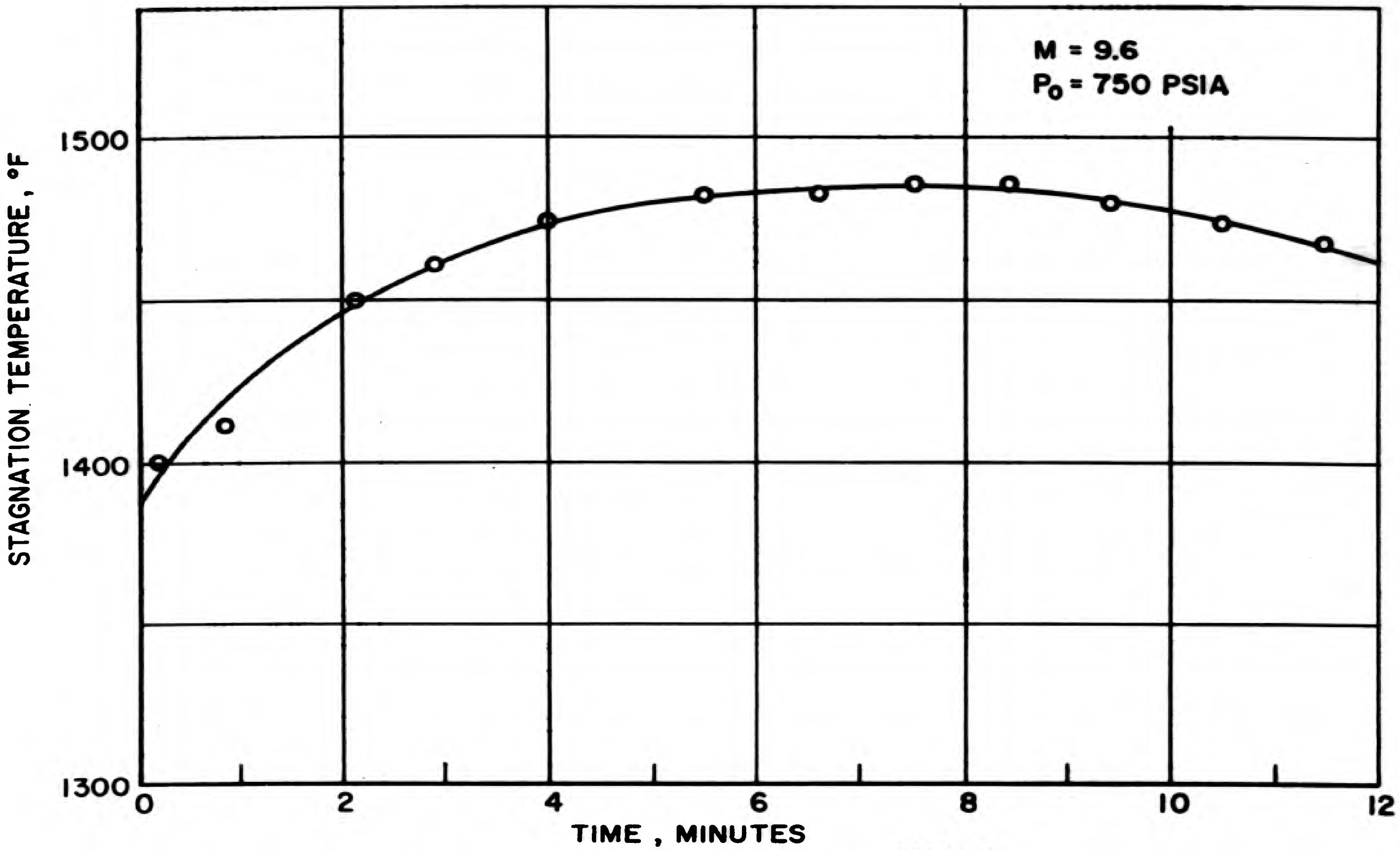

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Figure 8. A typical stagnation temperature-time plot

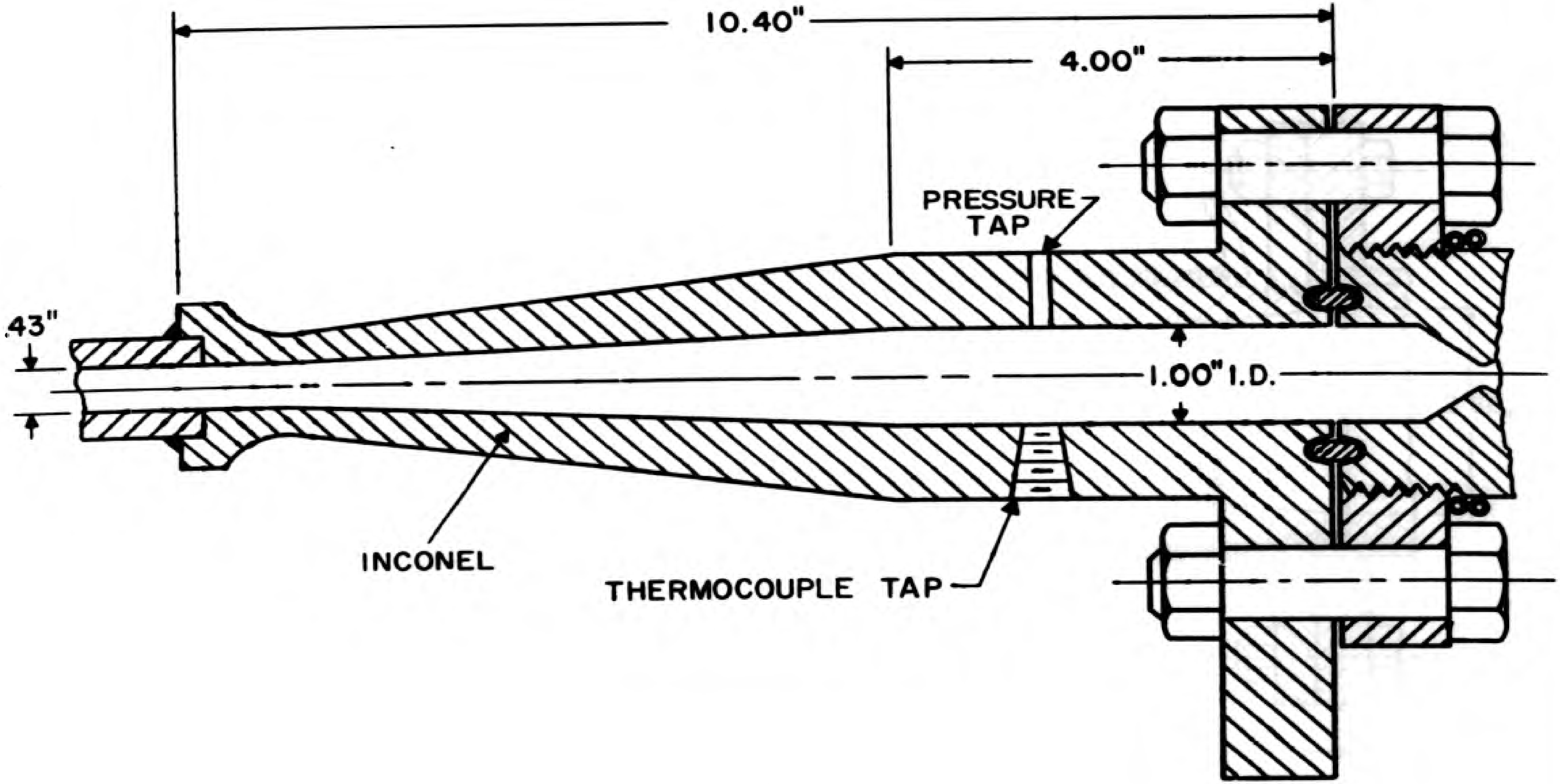

Figure 9. Settling chamber design

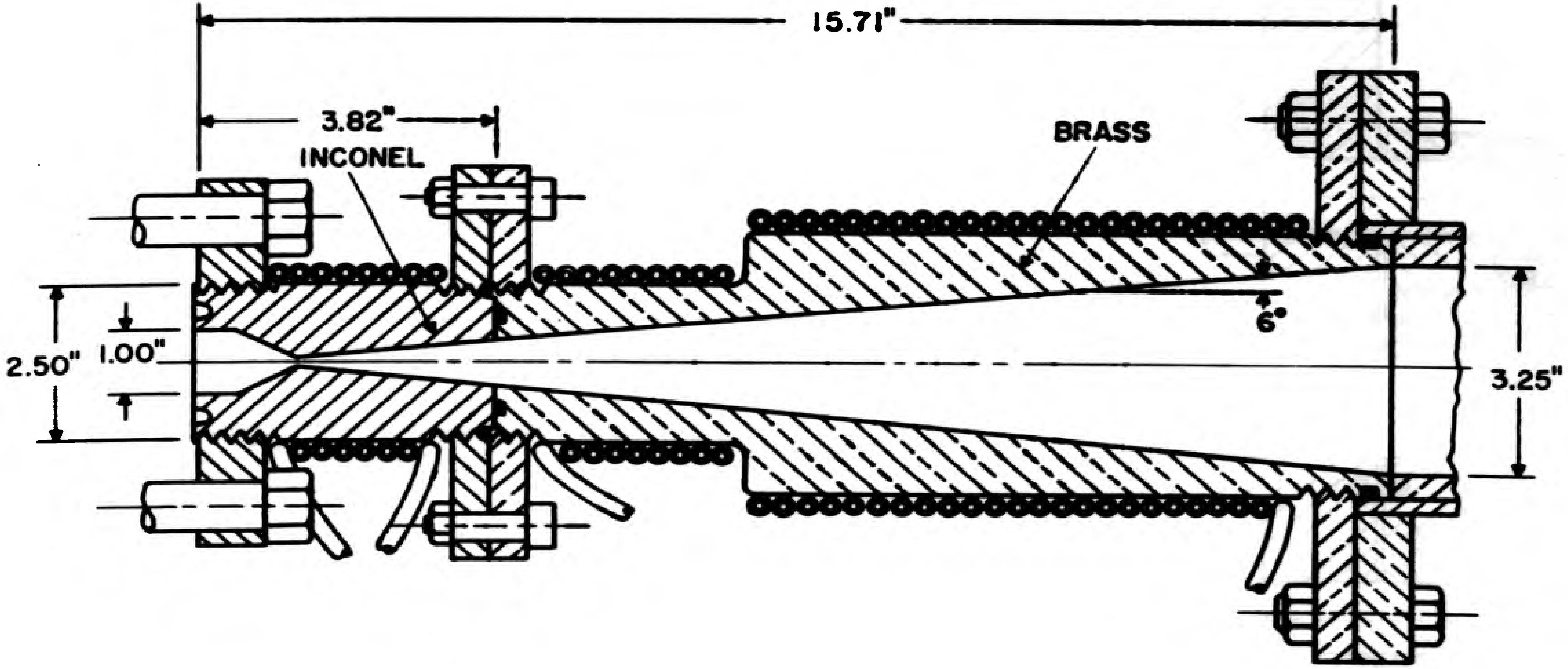

Figure 10. Conical nozzle assembly

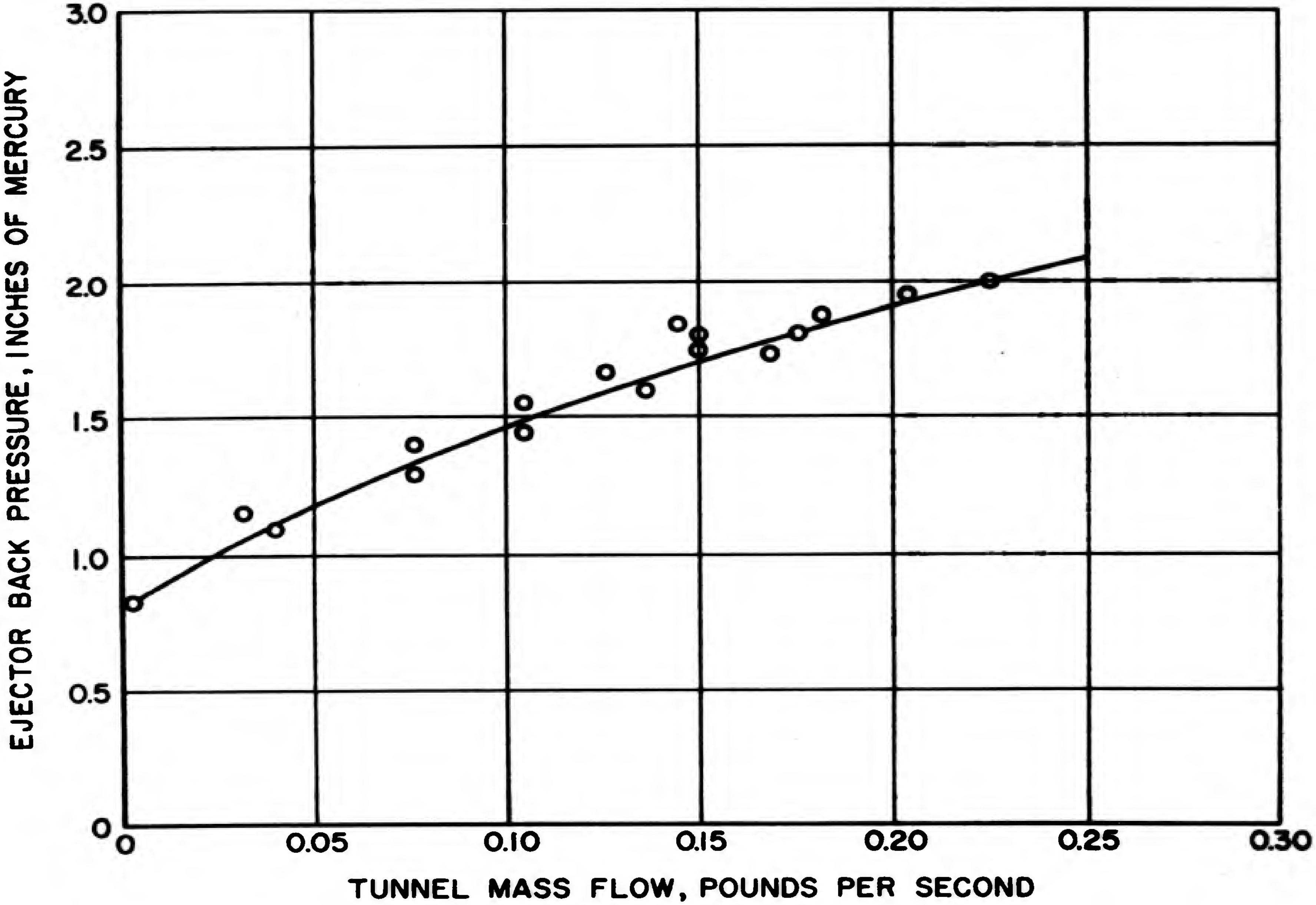

Figure 11. Ejector performance curve

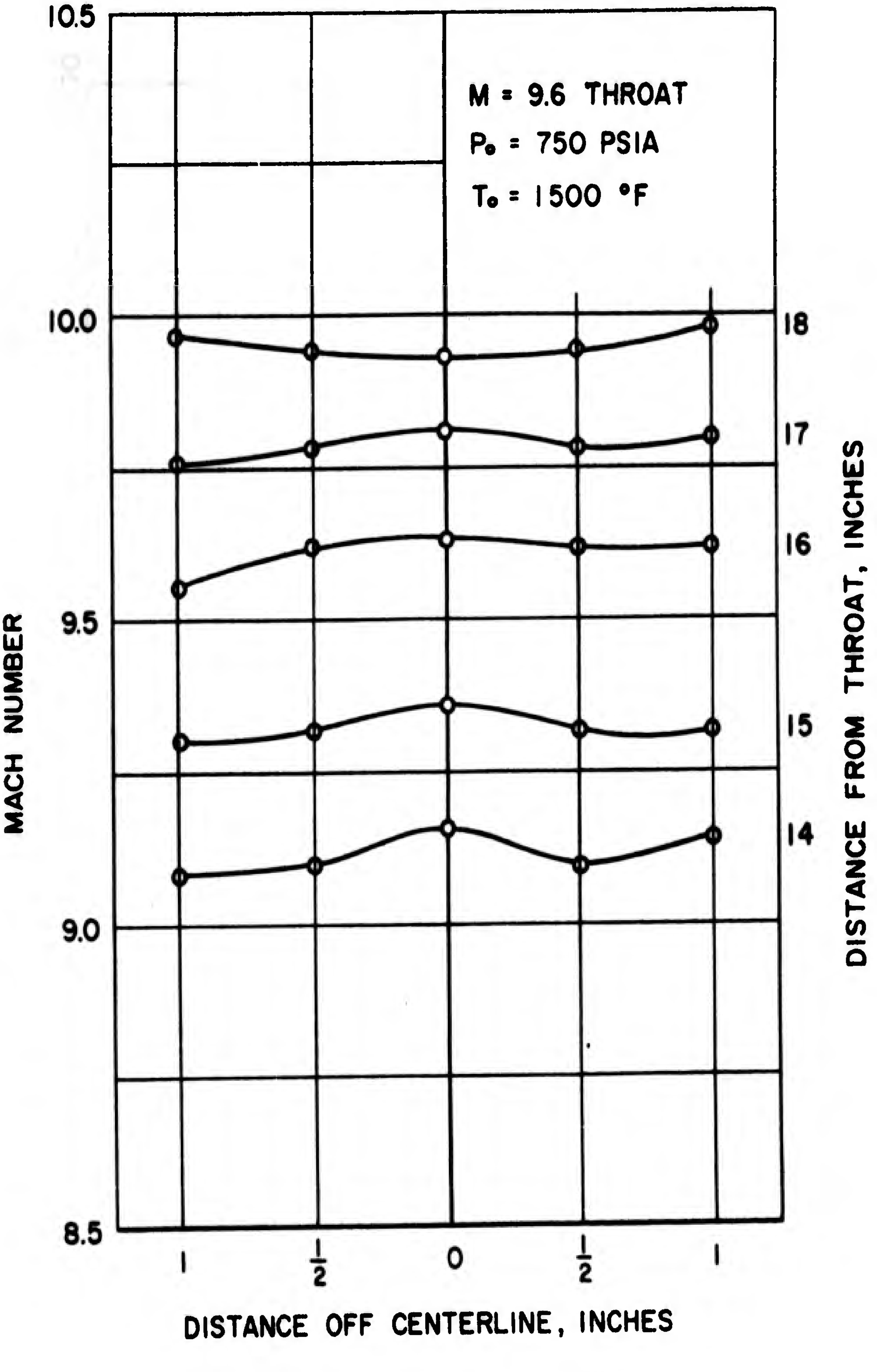

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Figure 12. Cross tunnel Mach number survey for the M ~ 9.6 throat section

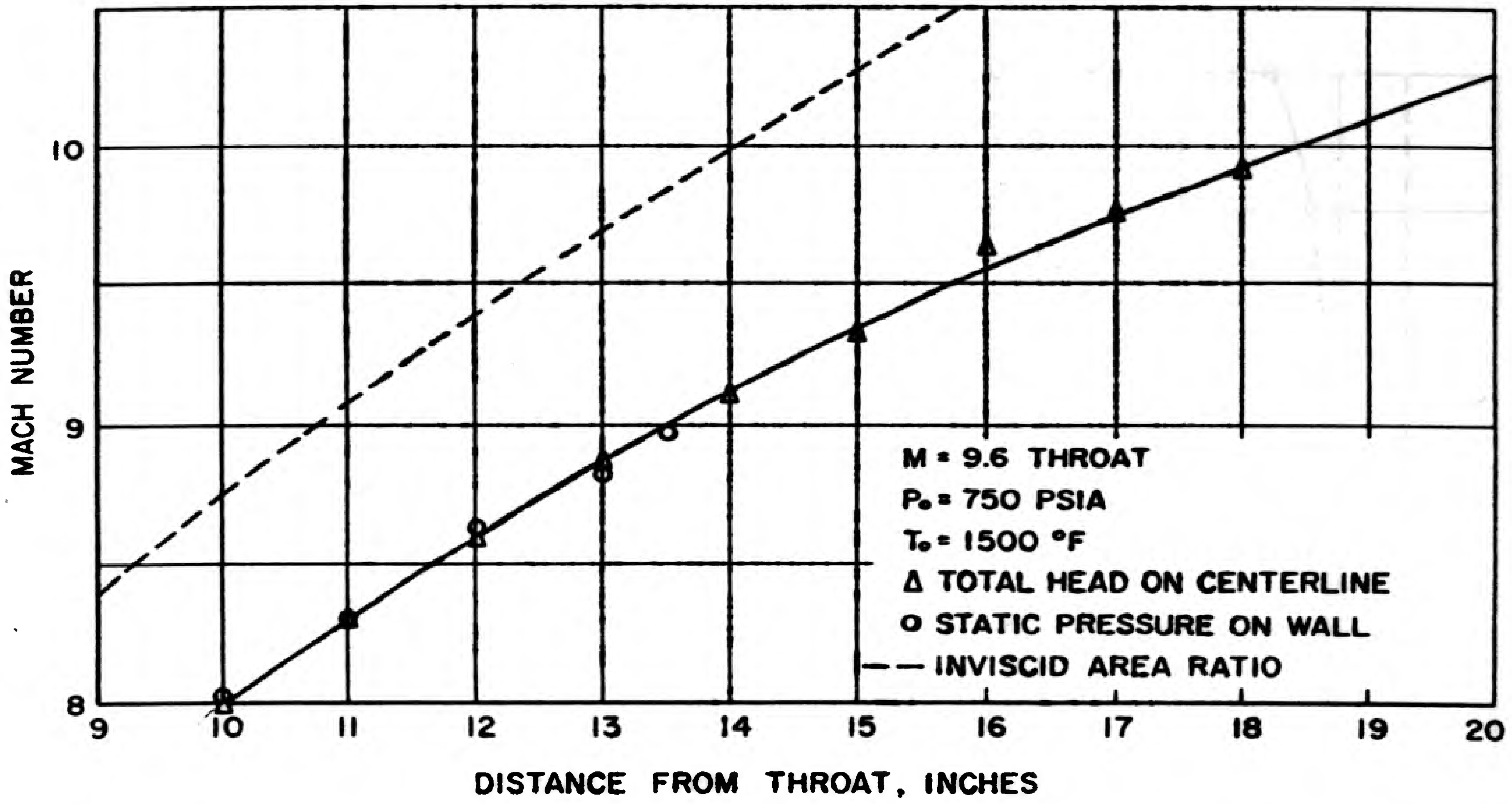

Figure 13. Centerline Mach number survey for the M ~ 9.6 throat section

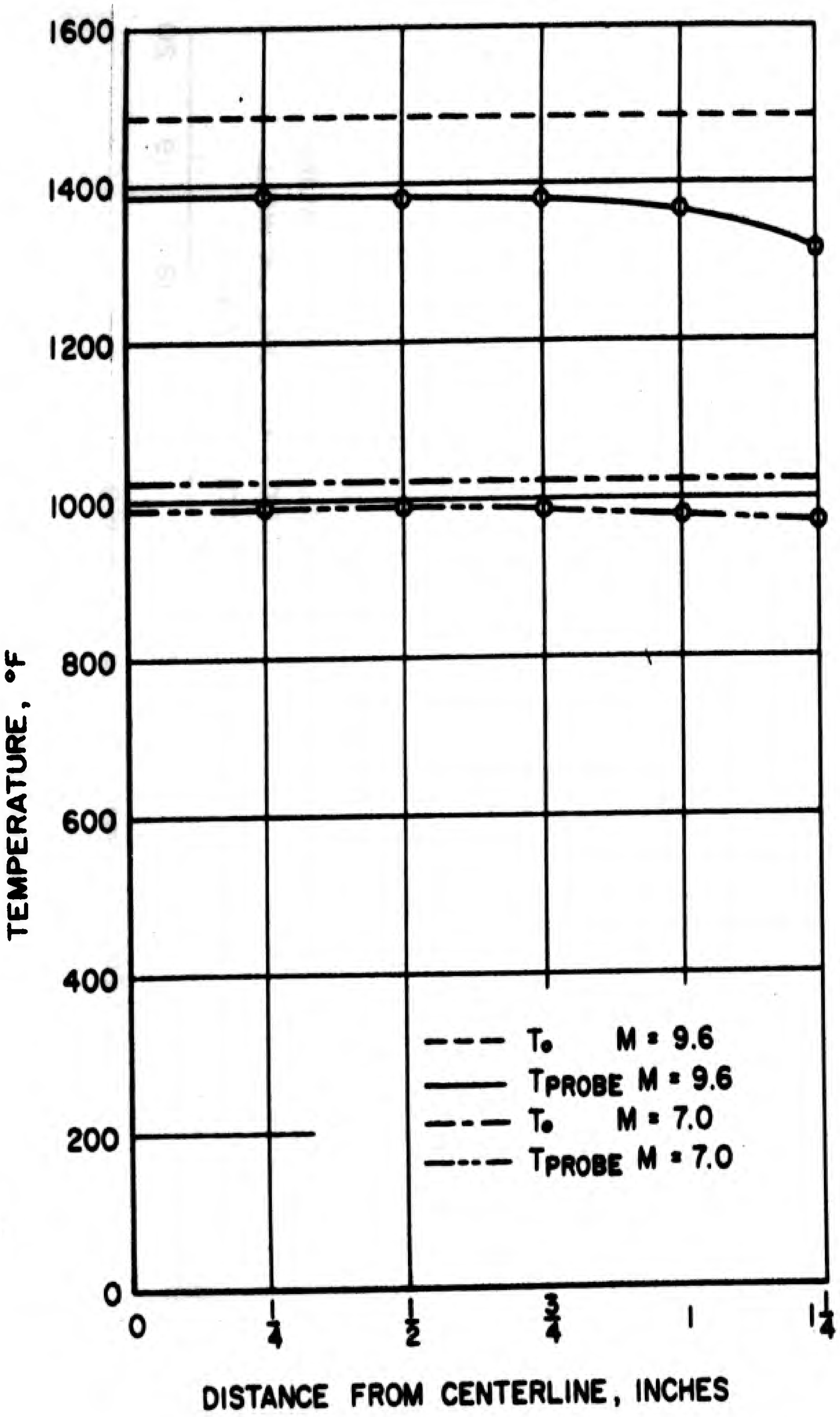

Figure 14. Total temperature survey for the M ~ 7 and M ~ 9.6 throat sections

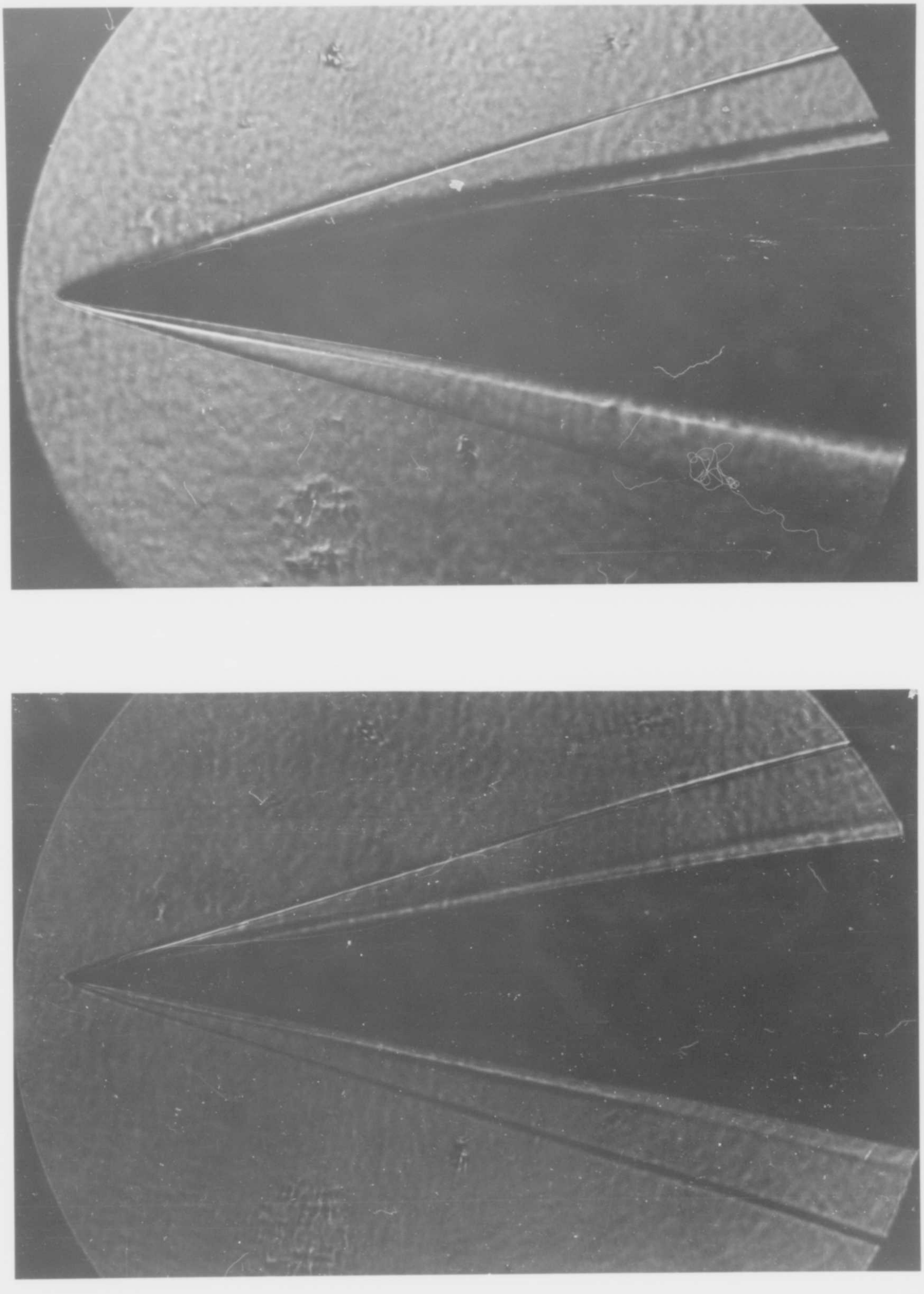

Figure 15. Schlieren (top) and shadowgraph (bottom) photographs of a 10° wedge at $M \sim 9.6$ in air