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RESEARCH MEMORANDUM

PERFORMANCE OF THREE HIGH-RECOVERY-FACTOR THERMOCOUPLE PROBES FOR ROOM-TEMPERATURE OPERATION

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NATIONAL ADVISORY COMMITTEE
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SUMMARY

Thermocouple probes have been designed to measure with small error the total temperature of gas moving at high velocities. Two major designs are presented: one is applicable to the construction of rakes and the other, of which there are two variations, can be used where exceptional accuracy is desired. The probes were calibrated in two jets; one jet exhausted into the atmosphere and the other into a pressure-controlled receiver.

These probes were capable of measuring 99.6 percent or more of the stagnation temperature at a free-stream Mach number of 1.0 and stagnation temperature of about 540° R. The probes were insensitive to misalinement to flow in the yaw angle up to ±30°. The error in measuring stagnation temperature was increased by about 0.1 percent for Mach numbers above 0.3 as the air density was reduced from 0.10 to 0.04 pound per cubic foot. The variation in recovery factor for four probes of a given design was very small at a given Mach number.

INTRODUCTION

When a temperature-sensing probe is inserted in a high-velocity gas stream, the temperature indicated is the summation of static or free-stream temperature and some portion of the theoretical temperature rise corresponding to the directed kinetic energy of the gas stream. The ratio of the actual temperature rise of the thermocouple above the free-stream temperature to the temperature rise that would be caused by complete adiabatic stagnation is termed "recovery factor." The ratio between the actual temperature indication and the true stagnation temperature represents the accuracy of indication of stagnation temperature by the thermocouple.

The accuracy of temperature indication is a function not only of recovery factor but also of the rate of heat flow by conduction and radiation from the thermocouple junction to the surroundings. The design requirements for high recovery and for low heat transfer are generally contradictory. A thermocouple located in a blind-end tube with the open end facing upstream would thus insure complete stagnation of the air surrounding the thermocouple. The response to a change in outside air temperature would be extremely sluggish, however, and the rate of heat loss by conduction along the thermocouple wires and supports would be large relative to the rate of heat conduction from the gas to the thermocouple.

The factors that affect the accuracy of temperature indication are dependent on local flow conditions of the gas stream, but in many thermocouple installations inaccurate knowledge of these local flow conditions may make application of flow calibrations uncertain. It is therefore desirable that the recovery of the thermocouple be sufficiently high so that any variation in recovery is negligible with change in flow conditions.

Three thermocouple designs that provide an accuracy greater than 99.5 percent of the stagnation temperature over the Mach number range of 0.3 to 1.0 were developed at the NACA Lewis laboratory and are reported herein. The probes were evaluated at a stagnation temperature of approximately 540° R. The designs represent a compromise between the requirements for high recovery and for low heat transfer to the surroundings.

DESCRIPTION OF PROBES

Two of the probes investigated, designated configurations A and B, are shown in figures 1(a) and 1(b), respectively. Configuration B is a simplified design of configuration A. In each case, a thermocouple made of 0.012-inch-diameter calibrated wire was placed in a diffuser-like chamber formed by two metal shields and a portion of the support tube. Gas entered the center slot, which was 0.025 inch wide by 0.5 inch long, and the velocity was reduced essentially to the stagnation value around the thermocouple. Complete stagnation was avoided by allowing the gas to escape through three bleed holes at the rear of the chamber. Gas also entered the additional chambers on each side of the thermocouple chamber and left through bleed holes. The temperature in these outside stagnation chambers approached that in the thermocouple chamber, so as to minimize the transmission of heat from the thermocouple to the inside metal shields by radiation or conduction.

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In the investigation, the diameter of the bleed holes of configuration A was varied from 0.010 to 0.040 inch. Two supports, one of Inconel and one of bakelite, were also investigated to determine the effect upon the error caused by conduction through the support. Also used with configuration A were two combinations of thermocouple-wire material, iron-constantan and chromel-alumel.

Configuration C (fig. 1(c)) was designed to measure temperature at a point and can be easily adapted to a rake. The probe has a calibrated iron-constantan thermocouple wire in a round, polished, diffuser-like chamber. This chamber is surrounded by another chamber that forms an additional stagnation region. The outside chamber has bleed holes on the side. The inside chamber has a bleed hole at the back of the support shaft. The insert in the support that contains the chambers is made of laminated silicone plastic, which limits the operating temperature of this probe to about 500° F.

CALIBRATION METHODS

The probes were calibrated in two air jets (fig. 2). The $3\frac{1}{2}$-inch-diameter free jet (fig. 2(a)) exhausted into the atmosphere. Calibration of the jet showed that the total pressure in the working region of the test section was equal to stagnation tank pressure within the measuring accuracy of a water manometer. The density at the test section did not increase more than 17 percent from the ambient value with an increase in Mach number. Most of the investigation was performed in this jet. The $2\frac{3}{4}$-inch-diameter jet (fig. 2(b)), which exhausted into a pressure-controlled receiver, was used to determine the effect of a large change in free-stream density upon the accuracy of stagnation temperature indication. This jet also had no measurable total-pressure loss between the point where the total pressure was measured during a run and the test section.

Total temperature of the jets was measured by thermocouples in the low-velocity regions upstream of the test sections as shown in figure 2. The difference between total and static temperature in this region was less than 0.2° F and, because the thermocouple used for this purpose had a relatively high recovery, the resultant deviation from total temperature was negligible. This reference probe was connected with the test probe in a series-opposition circuit. A potentiometer with a sensibility of 0.002 millivolt indicated a voltage that was proportional to the difference between reference temperature and test-probe temperature. Because only temperature differences were measured, the absolute accuracy and the zero drift of the potentiometer did not affect the measurement. The total temperature in both tunnels was approximately 80° F.

Recovery factor, in terms of the quantities actually measured, was calculated from

$$\text{recovery factor} = 1 - \left(\frac{T-t_i}{T-t}\right)$$

where

T total temperature, °R

t_i indicated probe temperature, °R

t static temperature, °R

For an isentropic expansion, the difference between total and static temperature $T-t$ was computed from

$$T-t = T\left[1-(p/P)^{\frac{\gamma-1}{\gamma}}\right]$$

where

p static pressure, absolute units

P total pressure, absolute units

γ ratio of specific heats, taken as 1.40

It should be noted that the difference between total and indicated temperature is attributed entirely to velocity effects.

The Mach number M was determined from static and total pressure at the test section, according to the relation for one-dimensional flow of a perfect gas

$$M = \sqrt{\frac{2}{\gamma-1}\left[(P/p)^{\frac{\gamma-1}{\gamma}} - 1\right]}$$

RESULTS AND DISCUSSION

The results are plotted in terms of recovery factor and the ratio of indicated to total temperature t_i/T. The ratio of indicated to total temperature is more representative of the actual error in measuring temperature than is the recovery factor.

The effect of varying the bleed-hole diameter on recovery factor and t_i/T is shown in figure 3. The results show that the hole diameter for maximum recovery factor varies with Mach number. If a hole diameter of 0.032 inches is selected, however, the indicated temperature will be within 0.035 percent of the maximum indicated temperature at each Mach number.

The effect of substituting bakelite in place of Inconel for the support tube is shown in figure 4. The probe with the low-thermal-conductivity bakelite support has a higher recovery than the probe with the Inconel support. The use of bakelite as a support material, however, will limit the operating-temperature range of the probe.

The effect of wire material is shown in figure 5 for the probe with the bakelite support. The probe with the lower-thermal-conductivity wire (chromel-alumel) had a higher recovery than the probe with iron-constantan wire.

Configuration B is a simplified design aimed toward reducing construction time and affording ease of insertion into a test unit. Because of the all Inconel construction, the probe can be used at elevated temperatures. This probe was designed using the information obtained with configuration A. Figure 6 shows the recovery factor and t_i/T of four probes of configuration B. Probes of this configuration indicate at least 99.8 percent of the stagnation temperature at a Mach number of 1.0. In the construction of probes of a given design, slight variations in sizes and positioning of parts will normally occur. From figure 6, the effect of constructional variations among four probes t_i/T is seen to be small at any Mach number.

The effect of misalinement in yaw between the probe and the airstream of the free jet is shown in figure 7. The ratio t_i/T is independent of yaw angle at a constant Mach number of 0.52 up to $\pm 30^{\circ}$ and decreases from 99.91 percent to approximately 99.7 percent at a yaw angle of $\pm 40^{\circ}$.

In normal use, this probe will be subjected to a large range of free-stream densities and velocities. The effect of free-stream density upon t_i/T and recovery factor of the probe is shown in figure 8. These data were obtained in the pressure-controlled jet. The free-stream density was maintained constant at 0.10 and 0.04 pound per cubic foot, and the Mach number was varied from 0.3 to 0.9. Higher recovery was obtained at the higher density. The ratio of t_i/T is about 0.1-percent lower for the lower-density as compared to the higher-density data.

The recovery factor and t_i/T calibration of two probes of configuration C are shown in figure 9. The data were taken in the free jet. One of the probes indicated 99.66 percent of the stagnation temperature at a Mach number of 0.9.

The effect of misalinement in yaw between this probe and the airstream of the free jet is shown in figure 10. The ratio t_i/T is independent of yaw angle up to $\pm 30^\circ$ at a Mach number of 0.88.

SUMMARY OF RESULTS

Three stagnating-type thermocouple probes were investigated in high-velocity airstreams. When the total temperatures of the airstreams were about 80° F, it was found that:

1. For configurations A and B:

(a) The thermocouple probes indicated 99.8 percent or more of the stagnation temperature at a Mach number of 1.0.

(b) Slight variations in construction of probes of a given design had a small effect upon the ratio of indicated to total temperature.

(c) The thermocouple probe was insensitive to misalinement to flow in the yaw angle up to $\pm 30^\circ$ at a Mach number of 0.52.

(d) The ratio of indicated to total temperature was reduced about 0.1 percent for Mach numbers above 0.3 as the air density was reduced from 0.10 to 0.04 pound per cubic foot.

2. A probe designed to measure temperature at a point indicated 99.66 percent of the stagnation temperature at a Mach number of 0.9.

Lewis Flight Propulsion Laboratory,
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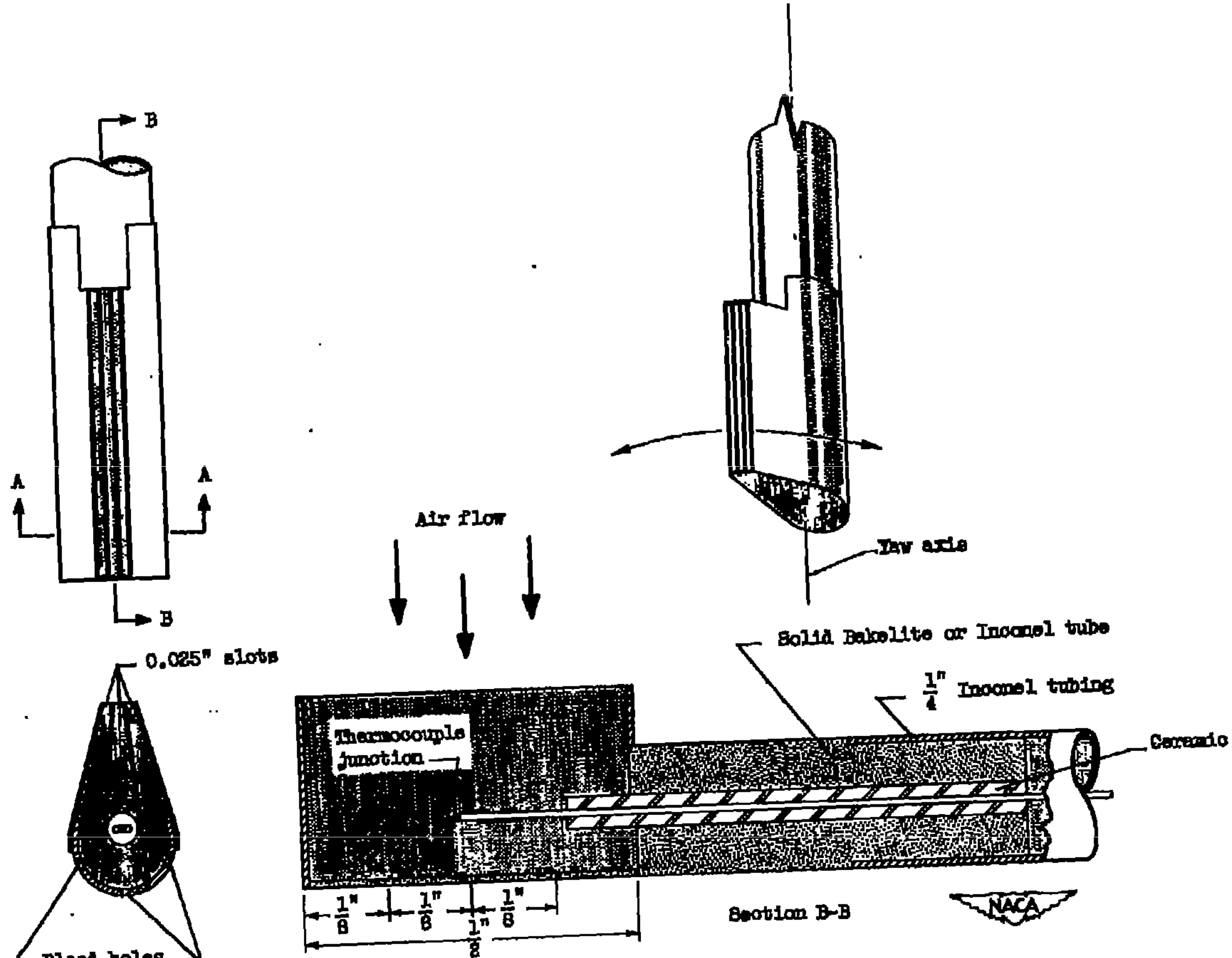
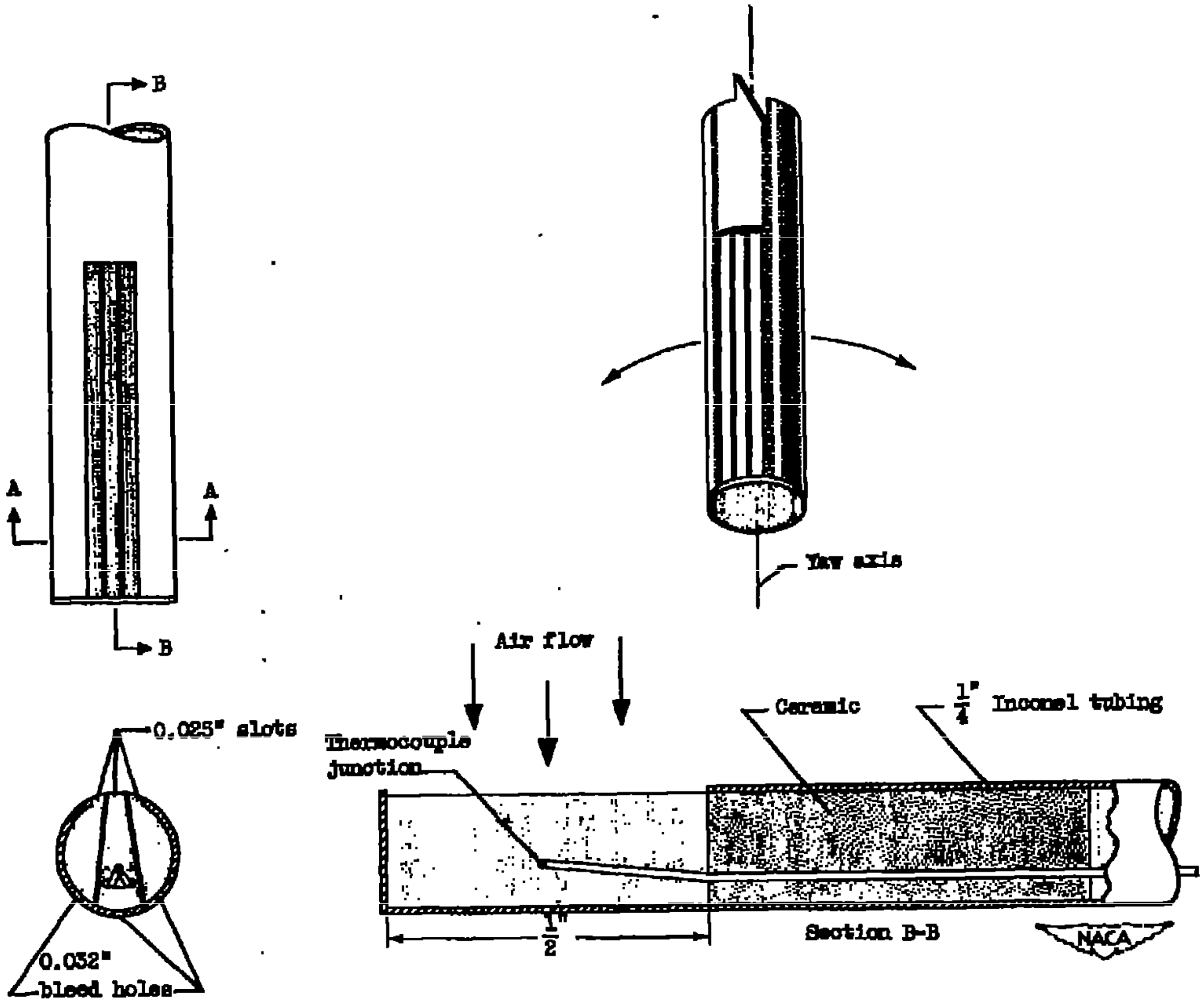


(a) Configuration A; original design.

Figure 1. - NACA high-recovery thermocouple probes.



Section A-A

(b) Configuration B; final design.

Figure 1. - Continued. NACA high-recovery thermocouple probes.

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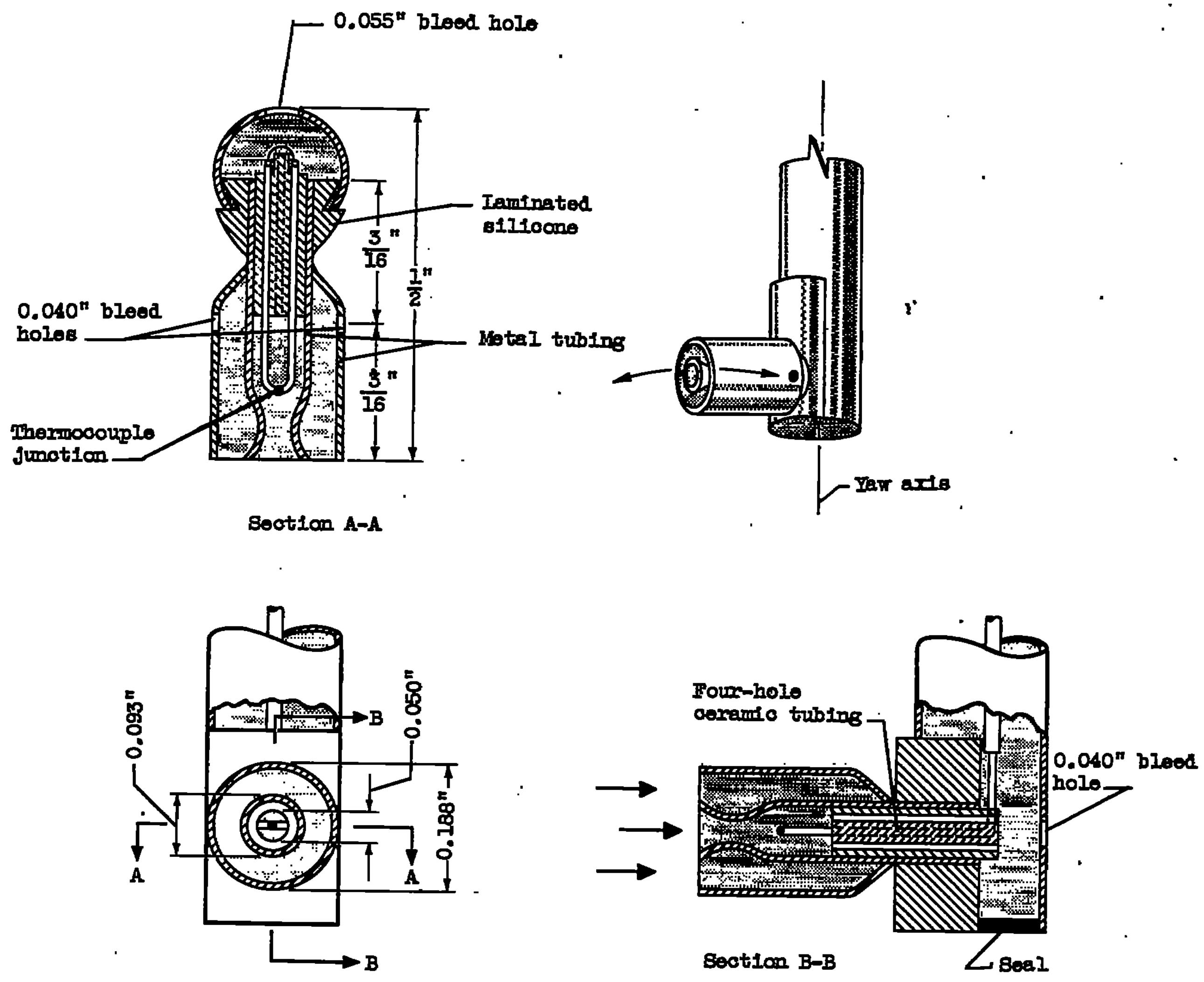

(c) Configuration C; design for measuring temperature at point.

Figure 1. - Concluded. NACA high-recovery thermocouple probes.

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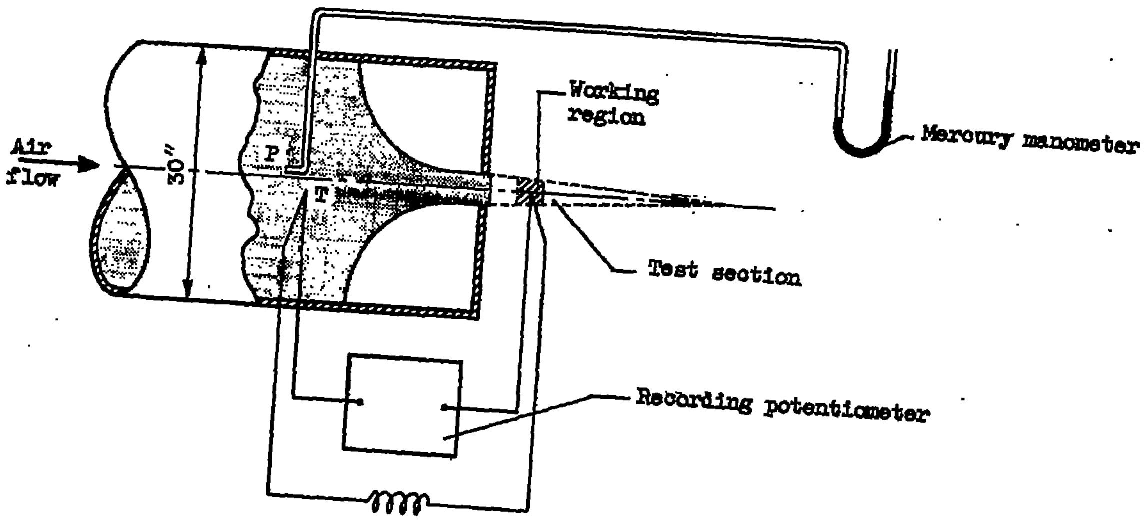
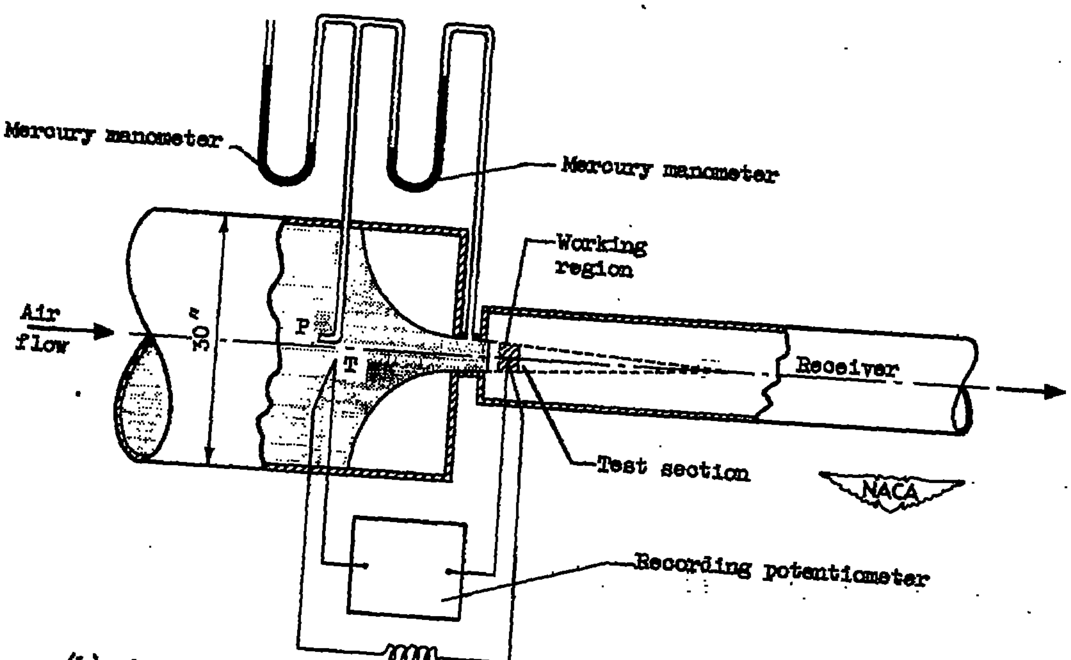


(a) Free jet; diameter, $3\frac{1}{2}$ inches.



(b) Jet exhausting into pressure-controlled receiver; diameter, $2\frac{3}{4}$ inches.

Figure 2. - Setup and instrumentation for calibration of NACA high-recovery thermocouple probes.

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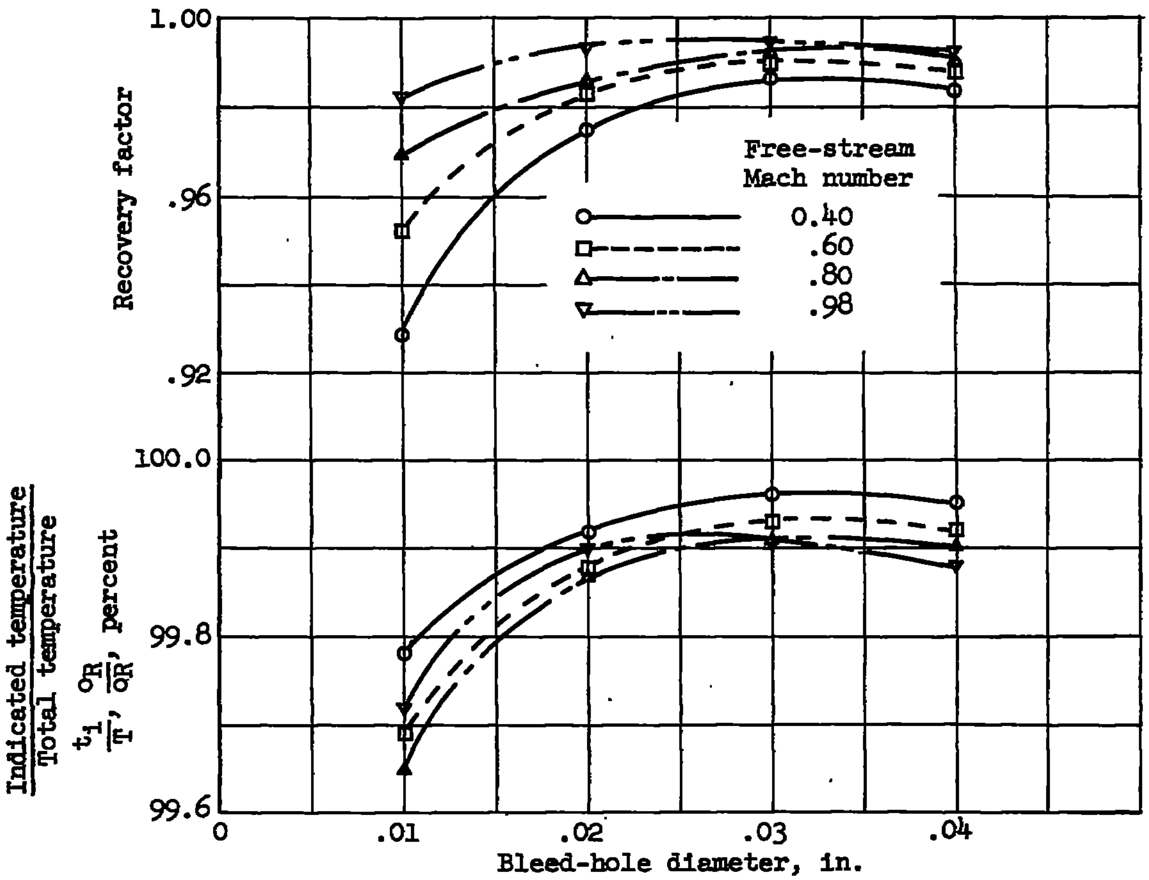

Figure 3. - Effect of bleed-hole diameter on recovery factor and ratio of indicated temperature to total temperature of chromel-alumel thermocouple probe with metal support in free jet. Configuration A.

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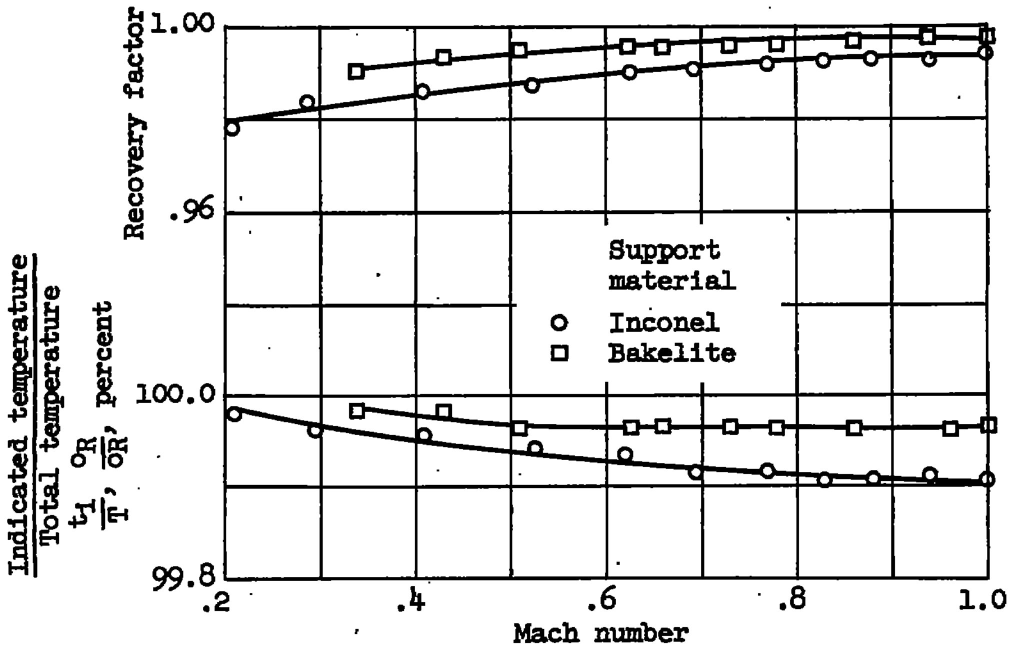

Figure 4. - Effect of support material on recovery factor and ratio of indicated temperature to total temperature of chromel-alumel thermocouple probe in free jet. Configuration A.

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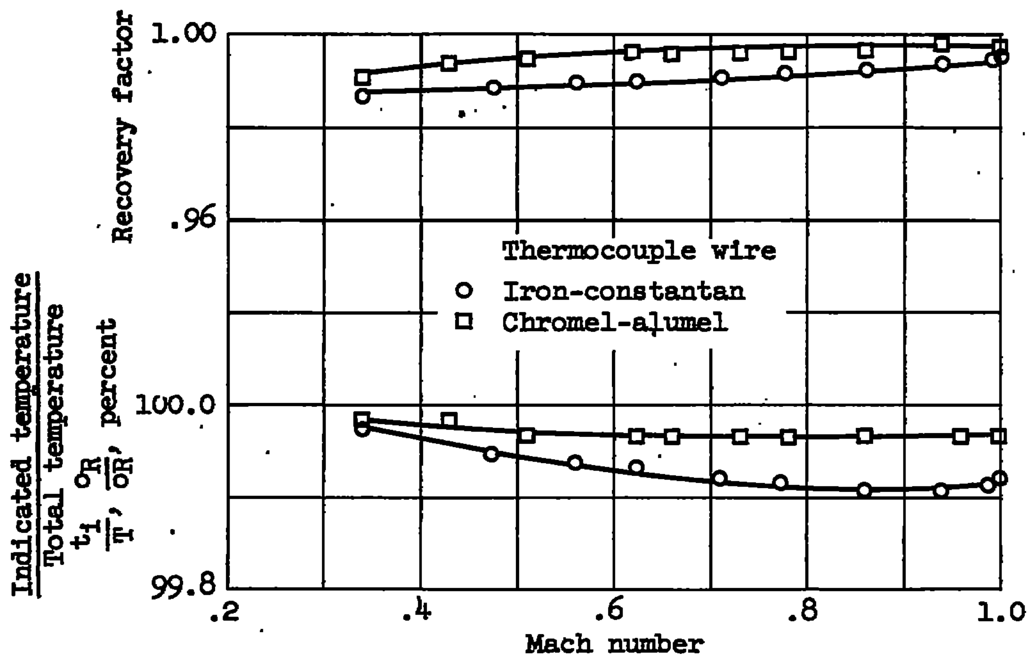

Figure 5. - Effect of thermocouple-wire material on recovery factor and ratio of indicated temperature to total temperature of two thermocouple probes with bakelite support in free jet. Configuration A.

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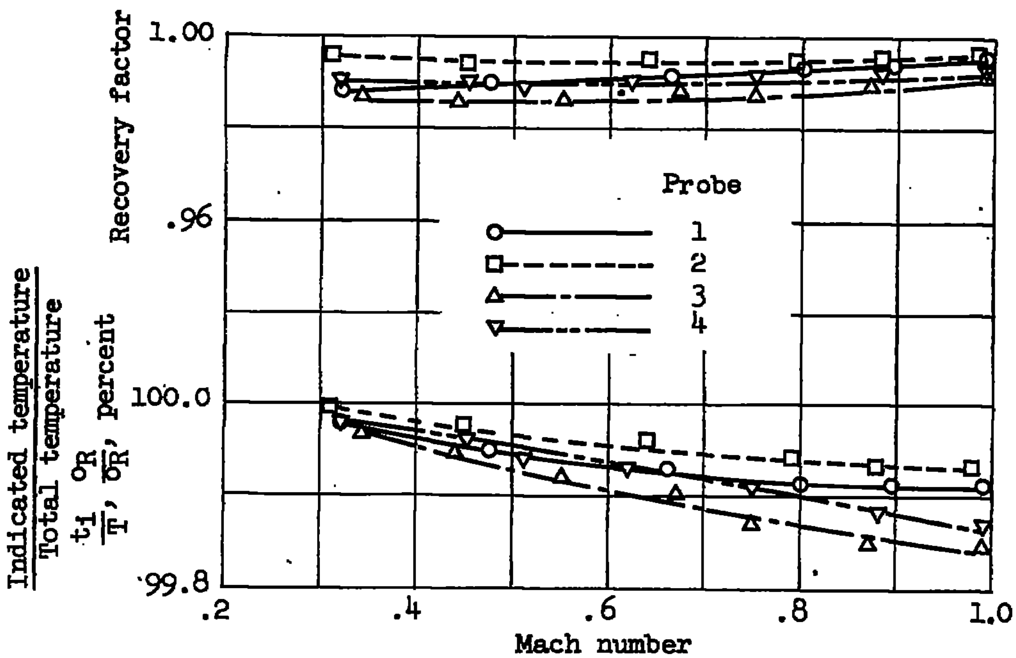

Figure 6. - Agreement of four similar chromel-alumel thermocouple probes as to recovery factor and ratio of indicated temperature to total temperature in free jet. Configuration B.

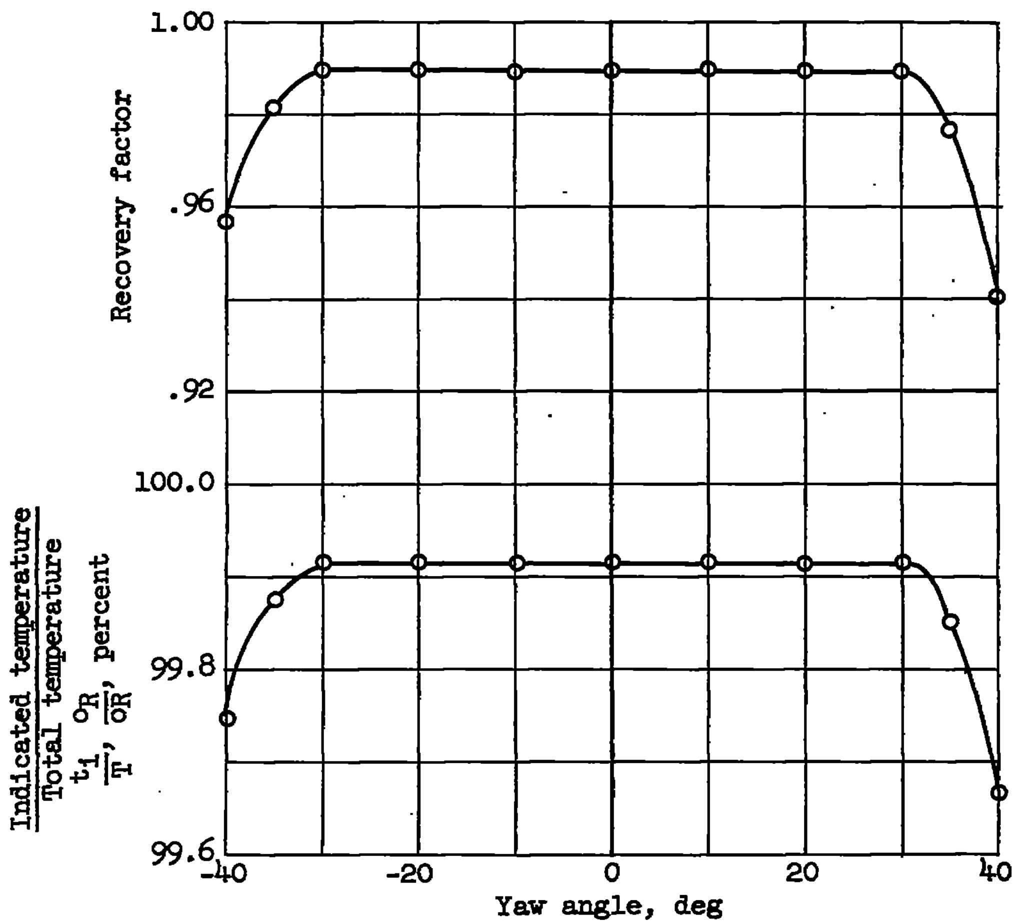

Figure 7. - Effect of yaw angle between chromel-alumel thermocouple probe and airstream on recovery factor and ratio of indicated temperature to total temperature in free jet. Configuration B; Mach number, 0.52.

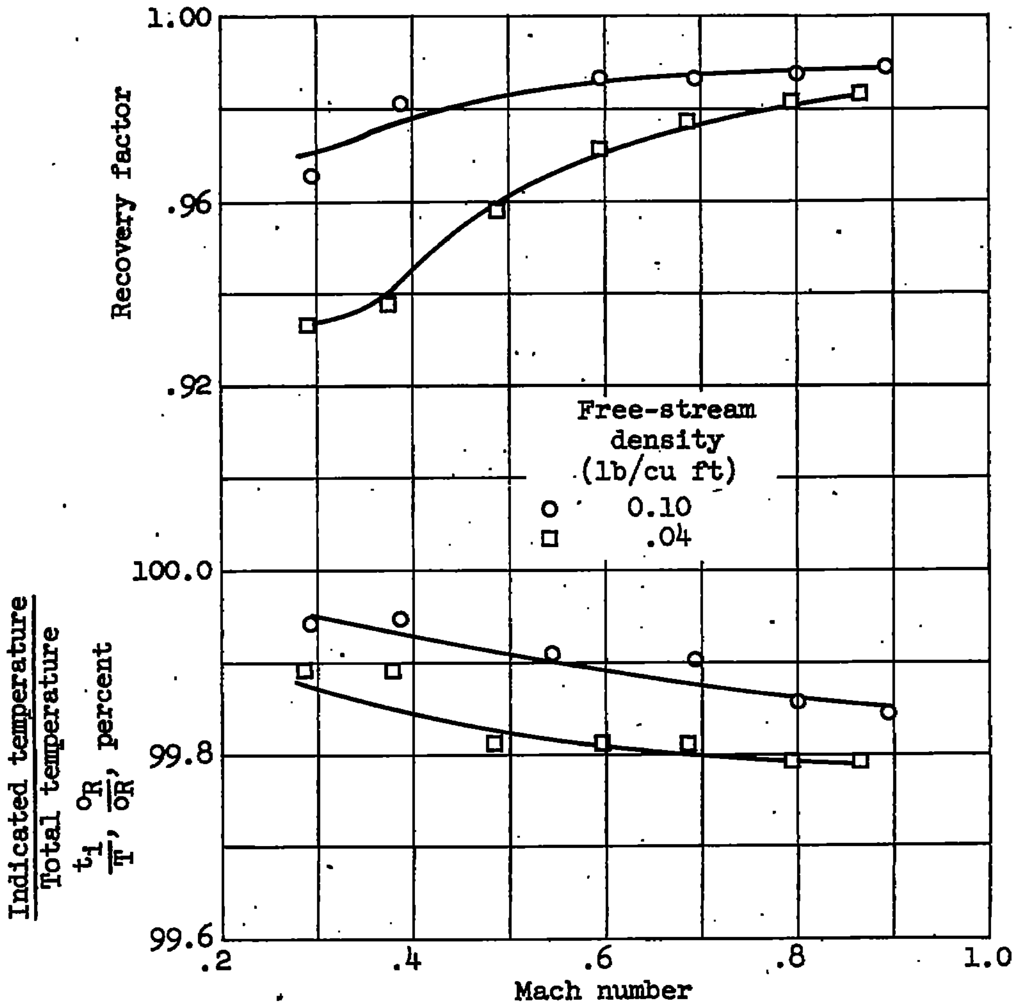

Figure 8. - Effect of free-stream density on recovery factor and ratio of indicated temperature to total temperature of chromel-alumel thermocouple probe in pressure-controlled jet. Configuration B.

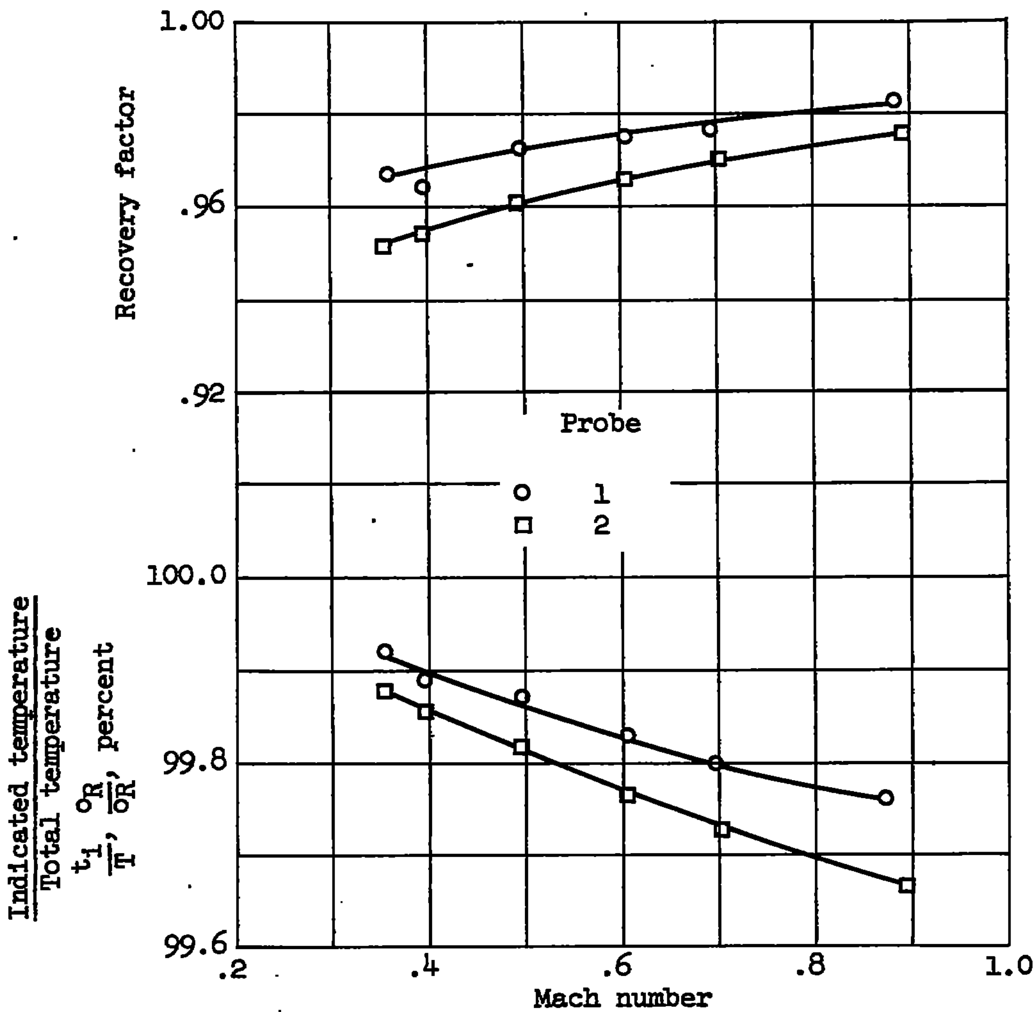

Figure 9. - Comparison of recovery factor and ratio of indicated temperature to total temperature for two iron-constantan thermocouple probes in free jet. Configuration C.

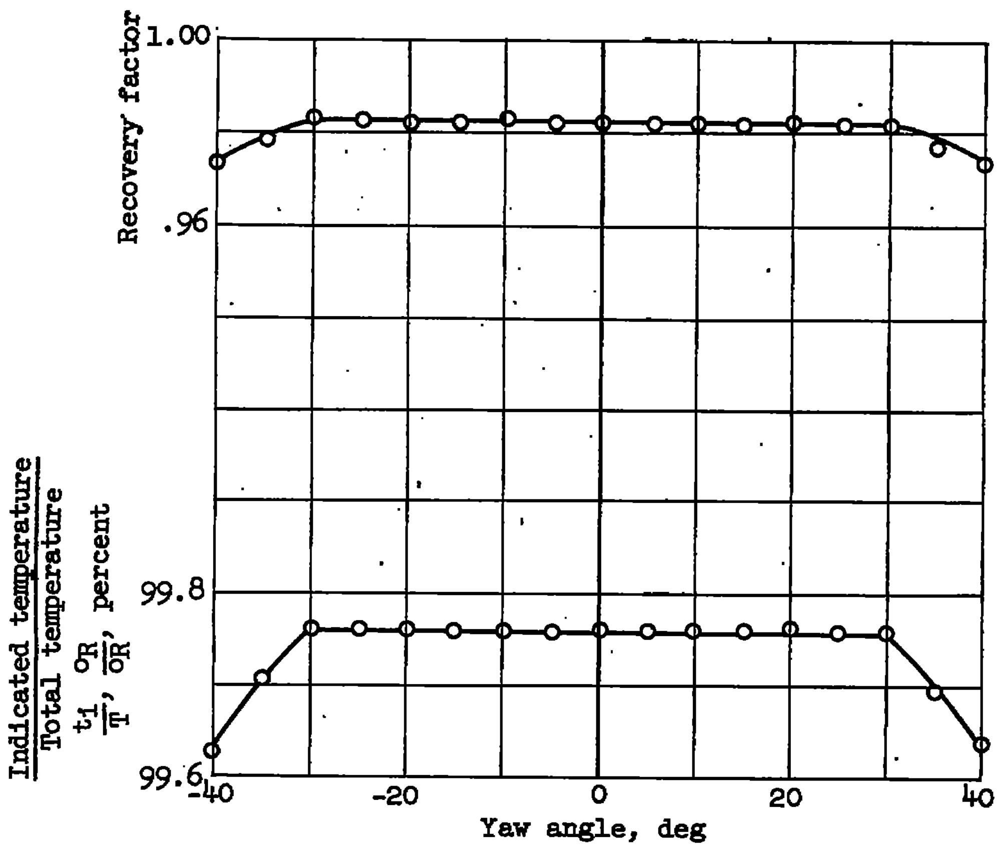

Figure 10. - Effect of yaw angle between iron-constantan thermocouple probe and airstream on recovery factor and ratio of indicated temperature to total temperature in free jet. Configuration C; Mach number, 0.885.