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TESTS OF TOTAL TEMPERATURE PROBES

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NATIONAL BUREAU OF STANDARDS

JUNE 1953

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TESTS OF TOTAL TEMPERATURE PROBES

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National Bureau of Standards

June 1953

*Power Plant Laboratory
Contract No. AF (33-616)53-1
RDO No. 540-20A*

Wright Air Development Center
Air Research and Development Command
United States Air Force
Wright-Patterson Air Force Base, Ohio

FOREWORD

This report was prepared by the National Bureau of Standards, Washington, D. C., under Contract No. AF (33-616)53-1. The contract was initiated under the research and development project identified by RDO No. 540-20A, and it was administered under the direction of the Power Plant Laboratory of Wright Air Development Center with Lt. A. M. Lapidés acting as project engineer.

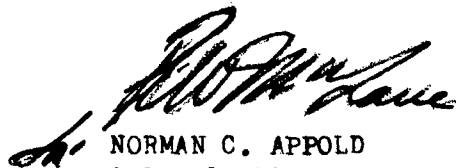
ABSTRACT

This report presents the results of performance tests of four total-temperature thermocouple probes designed for jet engine applications. The tests include the determination of rate of response and recovery factor, and the calibration of the thermocouples for the effects of radiation and conduction losses.

PUBLICATION REVIEW

The publication of this report does not constitute approval by the Air Force of the findings or the conclusions contained herein. It is published primarily for the exchange and stimulation of ideas.

FOR THE COMMANDER:



NORMAN C. APPOLD
Colonel, USAF
Chief, Power Plant Laboratory

INTRODUCTION

Four total-temperature type thermocouple probes designed for application in jet engine testing and operation were submitted by Fenwal Incorporated, Ashland, Massachusetts, for general performance and evaluation tests. Two of the probes were designed and manufactured by Fenwal while the other two were manufactured by Pratt and Whitney Co. The probes were subjected to tests to determine: (1) rate of response; (2) recovery factor; and (3) radiation and conduction effects.

DESCRIPTION OF TEST THERMOCOUPLES

The two thermocouples manufactured by Fenwal, Inc., shown in figure 1A, are identified by the designation Fenwal #77303-4, Engineering samples H-184 and H-185. The other two probes, shown in figure 1B, are identified as Pratt and Whitney #181796, Engineering samples H-203 and H-204. All four probes are of the total-temperature type with #18 gage Chromel-Alumel thermoelements insulated with swaged magnesium oxide. The sensing junction is bare and is located within a cup-type stagnation zone. The probes are provided with screw terminals of the thermocouple materials, the Chromel terminal being threaded for an 8-32 nut and the Alumel for a 10-32 nut. The probes are provided with metal mounting flanges. With the probe mounted such that the slotted stagnation cup faces directly upstream, the holes in mounting flange of Fenwal #77303-4 probe lie on a line parallel to the direction of gas flow. In the case of Pratt and Whitney #181796 probe, the holes in the mounting flange lie on a line at right angles to the direction of gas flow. A Fenwal probe #77303-2, not included in the present tests, has a flange orientation similar to Pratt and Whitney #181796 but in all other respects is identical to Fenwal #77303-4.

RESPONSE RATE TESTS

The rate at which a temperature-sensing device responds to a sudden change in the temperature of the medium in which it is immersed is an important factor in control applications. This is particularly true in the case of jet engine operation, where temperature changes may occur with extreme rapidity and where an increase beyond a predetermined operating limit may cause extensive damage to the engine.

When the temperature of a gas stream in which a thermocouple is immersed is increased instantaneously, the increase, ΔT , in the temperature of the sensing junction with time, t , thereafter is given by the equation

$$\Delta T = (T_2 - T_1)(1 - e^{-t/\tau}) \quad (1)$$

where T_1 = initial temperature of the junction
 T_2 = final steady temperature of the junction
 e = 2.7183, the base of the Napierian system of logarithms
 τ = a constant

From equation (1) we may write

$$\Delta T / (T_2 - T_1) = 1 - e^{-t/\tau} \quad (2)$$

It is apparent from equations (1) and (2) that the quantity τ has the dimensions of time, and that at time $t = \tau$, equation (2) becomes

$$\Delta T / (T_2 - T_1) = 1 - \frac{1}{e} = 0.632 \quad (3)$$

Thus, τ is the time required for the thermocouple junction to undergo 63.2% of the total change in temperature to which it is subjected instantaneously. The time τ , so defined is generally referred to as the characteristic time of the junction. Actually it is not a characteristic of the junction alone, but of the junction and the system in which it is immersed, so that the gas flow rate must be specified simultaneously with the characteristic time.

The apparatus used for subjecting a thermocouple junction to a sudden change in gas temperature is shown in figure 2. It consists essentially of an Inconel tube which can be held in place by a release pin but which upon removal of the pin, is pulled away by a spring. Thus, the junction is suddenly exposed to the hot gas stream flowing through the test section. While the Inconel tube is in position around the test junction, cooling air is forced through the tube to keep the junction at a selected low value. The emf of the thermocouple is recorded by means of a direct-inking oscillograph, the amplitude of the record being proportional to thermocouple emf. A time scale is provided by either the continuous 60-cycle oscillations of the pen, or by the known rate at which chart paper moves.

The response rates of the four test probes were determined at gas flow rates of 2, 4, and 6 lbs/sec ft². A typical oscillograph record is shown in figure 3A, and a large scale plot of the time-temperature relation is shown in 3B. A summary of the observed values of characteristic time is given in table I.

RECOVERY FACTOR TESTS

When an immersion-type instrument, such as a thermocouple, is used to measure the temperature of a gas moving at a velocity of about 300 ft/sec or higher, the thermal effect of the impact of the gas molecules against the sensing element becomes significant if an accurate measurement of the gas temperature is to be made. Since the magnitude of the impact effect increases as the square of the velocity, errors of considerable magnitude may result at high velocities unless impact effects are taken into account.

The effectiveness of a particular probe in indicating the total temperature of a high-velocity gas stream is expressed by its recovery factor, r , defined as:

$$r = (T_i - T_s)/(T_t - T_s) \quad (4)$$

where T_i = temperature indicated by the thermocouple junction
 T_s = static temperature of the gas
 T_t = total temperature of the gas

The recovery factor tests were carried out in the apparatus shown diagrammatically in figure 4. Air is supplied by two Roots-Cornerville centrifugal blowers in series, each having a capacity of 5000 cu ft of free air per min. at a pressure of 5 lbs/in² gage. The air flows through a straight 12-foot length of 12-in. pipe before discharging through a 4-in. nozzle to the atmosphere. A cup-type total-temperature thermocouple is mounted in the 12-in. pipe, one foot upstream from the nozzle entrance. A total-pressure tube is also located in the pipe one foot upstream from the nozzle.

The probe under test is supported in the air stream at the nozzle discharge with the inlet port of the probe on the nozzle axis. The terminal end of the probe is mounted in an aluminum block provided with an electric heating coil. During a test, the power supplied to the heating coil is adjusted until the temperature of the block, and hence also that of the terminal end of the test thermocouple, is identical with that indicated by the junction of the test couple. Under this condition, heat losses from the junction by conduction along the thermocouple support tube are eliminated.

From the energy considerations applicable to a reversible adiabatic process, such as the flow of air through the nozzle used in the present system, it can be shown that the following relations hold at the nozzle discharge

$$T_s = T_t (p_t/p_s)^{(\gamma - 1)/\gamma} \quad (5)$$

$$T_t - T_s = V^2/2gJc_p \quad (6)$$

$$M = V/c \quad (7)$$

$$c^2 = \gamma gRT_s \quad (8)$$

where T = temperature in degrees Rankine
 p = absolute pressure
 C_p = heat capacity at constant pressure = 0.24 Btu/lb °F
 γ = ratio of specific heats = 1.4 for air under present test conditions
 g = acceleration of gravity = 32.2 ft/sec²
 J = mechanical equivalent of heat = 778 ft lb/Btu
 V = velocity in ft/sec
 M = Mach number
 c = velocity of sound
 R = gas constant = 53.3 ft lb/lb °F

The subscripts s and t refer to static and total conditions.

Since the total temperature and total pressure remain constant in the adiabatic expansion and compression of a perfect gas, the values of T_t and p_t observed upstream from the nozzle are applicable at the nozzle discharge. Since the nozzle discharges to the atmosphere, the static pressure, p_s , at the test thermocouple is the prevailing barometric pressure.

Thus from the observed values of T_t , $T_t - T_i$, p_t and p_s , the values of T_s at the test thermocouple, and hence also its recovery factor can be calculated from the above equations. The value of recovery factor for a given probe was found to be independent of velocity over the range $M = 0.2$ to $M = 0.7$. The test data are summarized in table II.

CALIBRATION TESTS

The temperature attained by a thermocouple junction immersed in a stream of hot gas is seldom identical with the true temperature of the gas, but instead is characteristic of a steady state at which the rate of heat transfer from the gas to the junction by convection is equal to the rate of heat transfer from the junction to the surroundings by radiation and conduction. The conduction effect can usually be made reasonably small by proper attention to the mechanical design of a thermocouple unit. In gas turbine and jet engine applications the

effect of radiation losses on the temperature indicated by a thermocouple is of major importance. For accurate measurements, it is necessary to evaluate the radiation correction in terms of the indicated gas temperature for the range of gas flows and wall temperatures prevailing in service.

Calibration tests to determine the combined effects of thermal radiation and conduction were carried out on one probe of each type namely: Fenwal #77303-4 (H-184) and Pratt and Whitney #181796 (H-204). The tests consisted in comparing the indication of each probe with the indications of two silver-shielded Chromel-Alumel junctions which had previously been calibrated against a radiation-compensated laboratory standard. The silver-shielded reference standards were made from samples of Chromel and Alumel supplied by Fenwal from the same lots of wire used in Fenwal test probes #77303-4. The arrangement of the test equipment for the calibration tests is shown in figure 5.

The tests of the thermocouples were made with gas temperatures ranging from 1000°F to 1500°F, wall temperatures from 800°F to 1200°F, and with gas flow rates of 2, 5, and 8 lb/sec ft². The calibration data are summarized in table III. It is believed that the corrections for radiation and conduction losses given in the table are accurate to $\pm 5^\circ\text{F}$ when the corrections are less than 20°F and to one fourth of the correction when the latter exceeds 20°F.

Combustion Section
National Bureau of Standards
Washington, D. C.
June 10, 1953

Table I

Summary of Response Rate Tests

Thermocouple Identification	Characteristic Time - Seconds at flow rates in lb/sec ft ²		
	2	4	6
Fenwal #77303-A			
Sample H-184	17.1	12.2	9.7
Sample H-185	15.1	10.1	7.7
Pratt and Whitney #181796			
Sample H-203	16.2	12.1	9.8
Sample H-204	17.6	12.3	9.4

Table II

Summary of Recovery Factor Tests

Thermocouple Identification	Recovery Factor M = 0.2 to M = 0.7
Fenwal #77303-4	
Sample H-184	0.98 ₂
Sample H-185	0.98 ₆
Pratt and Whitney #181796	
Sample H-203	0.99 ₀
Sample H-204	0.99 ₀

Table III. Calibration of Thermocouple for
Radiation and Conduction Effects

Gas Temp. °F	Wall Temp. °F	Indicated Temperatures - Degrees Fahrenheit							
		Pratt and Whitney #181796				Fenwal #77303-4			
		at flow rates in lb/sec ft ²				at flow rates in lb/sec ft ²			
		2	4	6	8	2	4	6	8
1500	1500	1500	1500	1500	1500	1500	1500	1500	1500
1500	1400	1473	1481	1484	1487	1467	1476	1481	1484
1500	1300	1449	1464	1471	1475	1439	1457	1465	1470
1500	1200	1429	1450	1459	1465	1416	1441	1452	1458
1500	1100	1413	1438	1450	1456	1398	1428	1442	1449
1500	1000	1401	1429	1443	1450	1385	1419	1435	1443
1400	1400	1400	1400	1400	1400	1400	1400	1400	1400
1400	1300	1377	1384	1387	1389	1374	1382	1385	1387
1400	1200	1357	1370	1375	1379	1351	1365	1372	1376
1400	1100	1340	1358	1365	1370	1331	1351	1360	1366
1400	1000	1325	1347	1357	1362	1314	1339	1350	1357
1300	1300	1300	1300	1300	1300	1300	1300	1300	1300
1300	1200	1279	1285	1288	1289	1276	1283	1286	1288
1300	1100	1261	1272	1278	1281	1256	1269	1274	1278
1300	1000	1247	1262	1269	1274	1239	1257	1265	1270
1200	1200	1200	1200	1200	1200	1200	1200	1200	1200
1200	1100	1182	1187	1190	1191	1180	1186	1188	1190
1200	1000	1167	1177	1181	1184	1163	1174	1178	1181
1200	900	1155	1168	1174	1178	1148	1163	1170	1174
1100	1100	1100	1100	1100	1100	1100	1100	1100	1100
1100	1000	1086	1090	1091	1093	1084	1088	1090	1092
1100	900	1073	1081	1084	1087	1069	1078	1082	1085
1100	800	1062	1073	1078	1081	1056	1069	1075	1078
1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
1000	900	988	991	993	994	986	990	992	993
1000	800	977	984	987	989	974	982	985	987

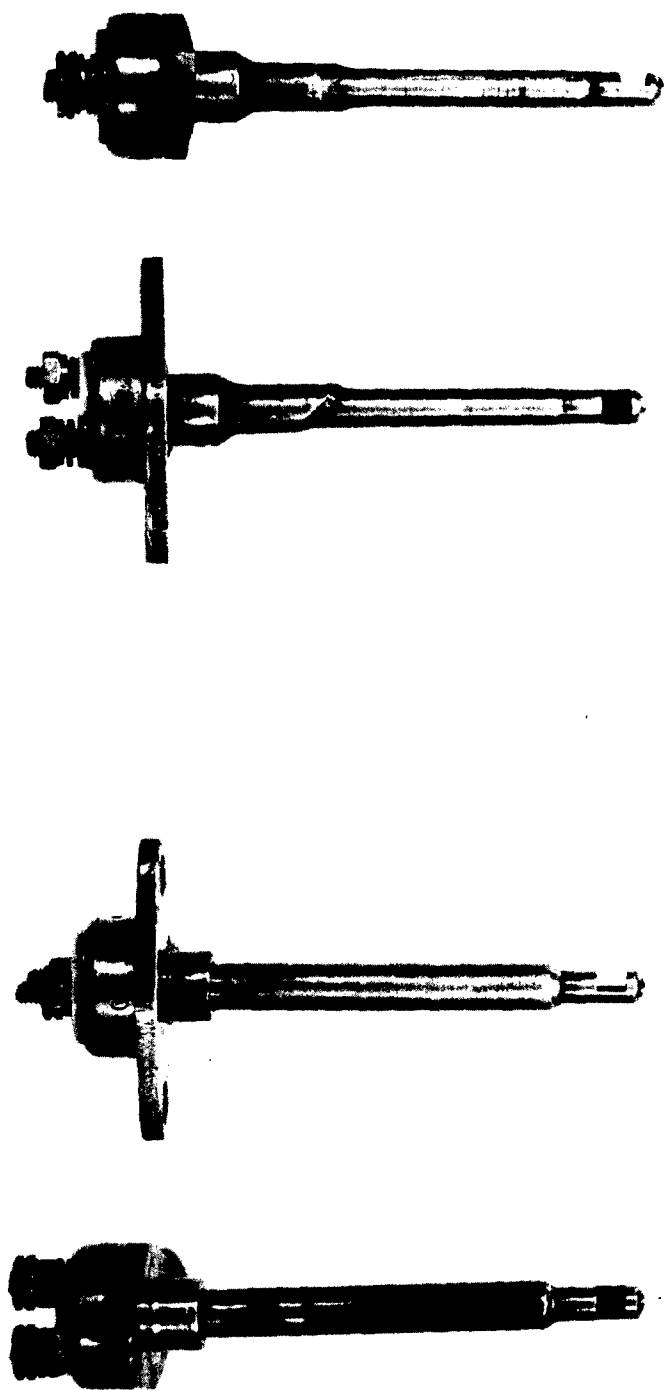


FIGURE 1

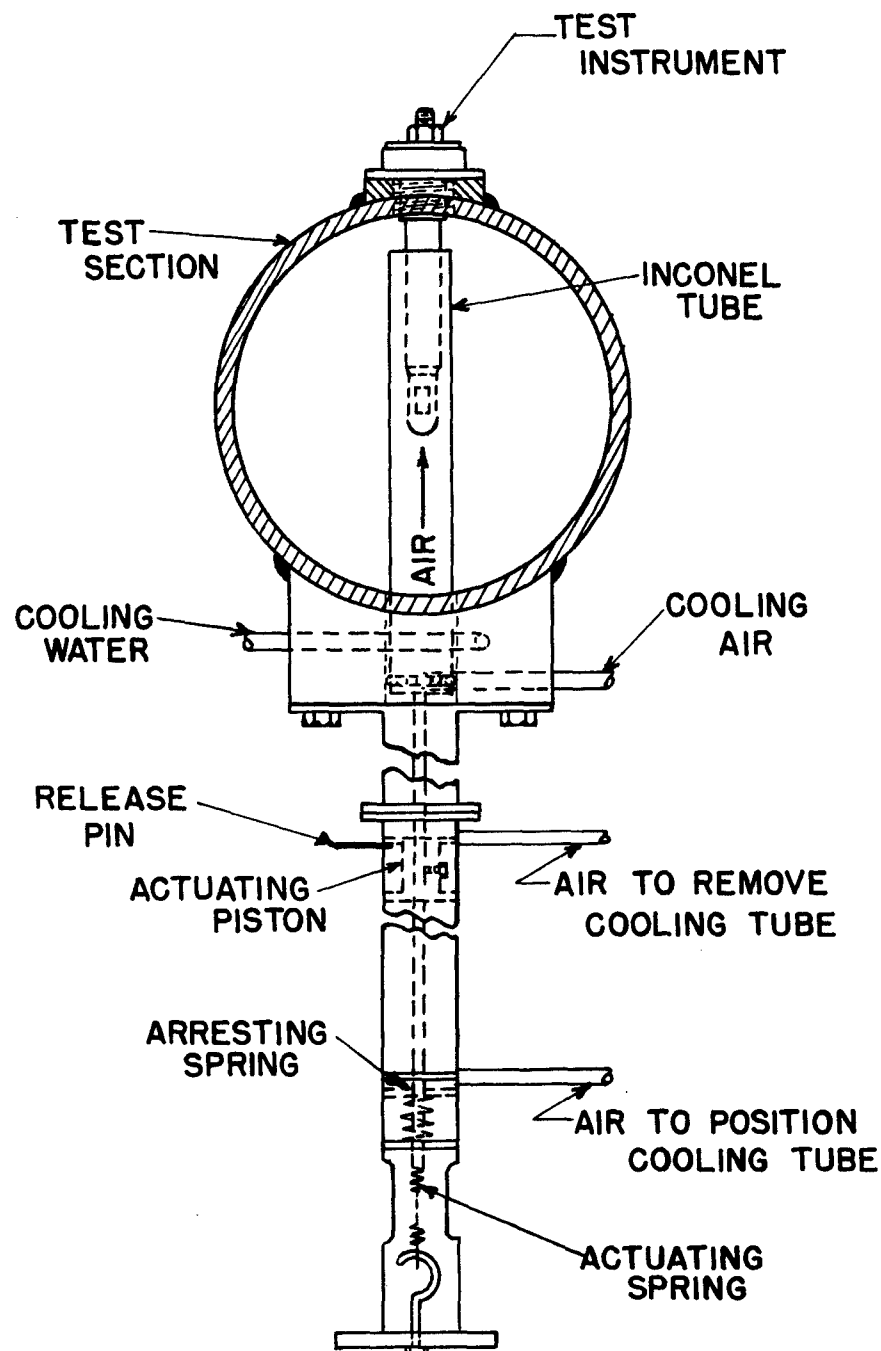
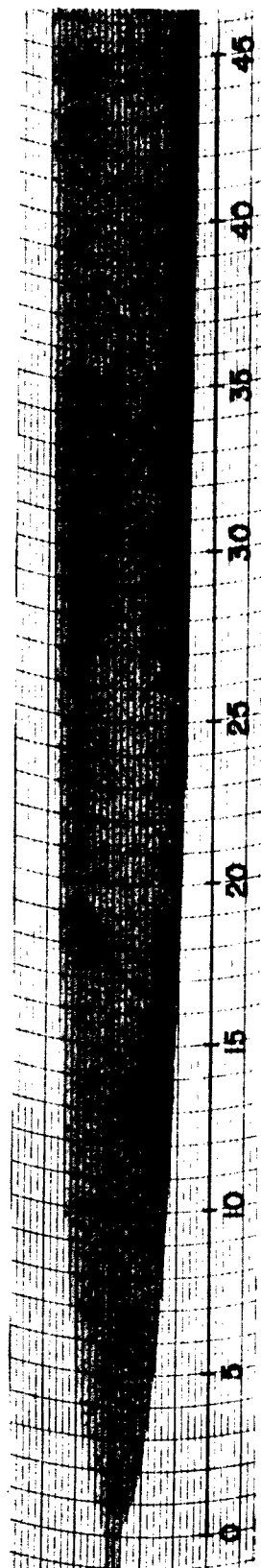
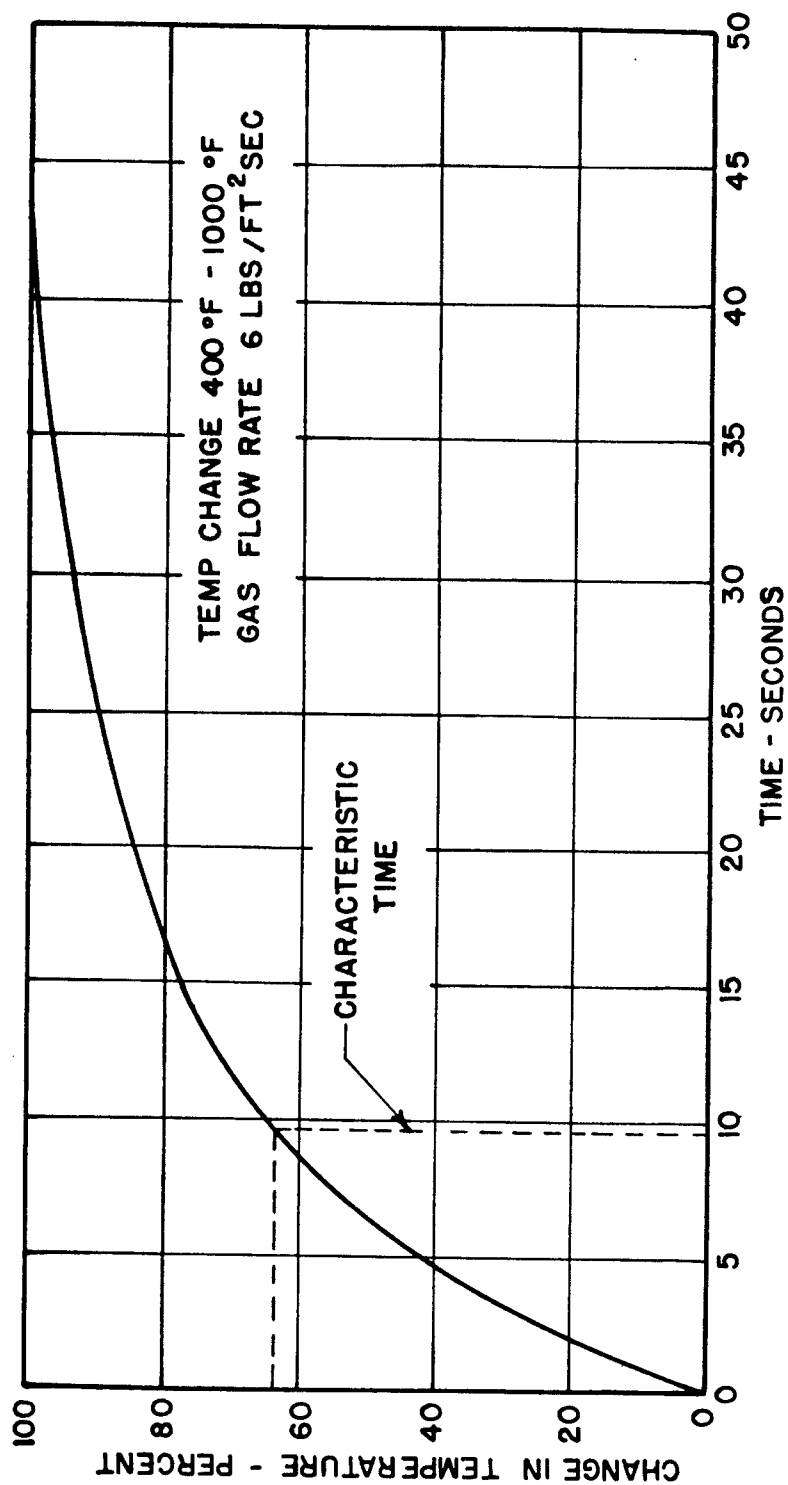


FIGURE 2 APPARATUS FOR SUBJECTING THERMOCOUPLE JUNCTIONS TO SUDDEN CHANGES IN GAS TEMPERATURE



A. OSCILLOGRAPH RECORD



B. RESPONSE CURVE

FIGURE 3

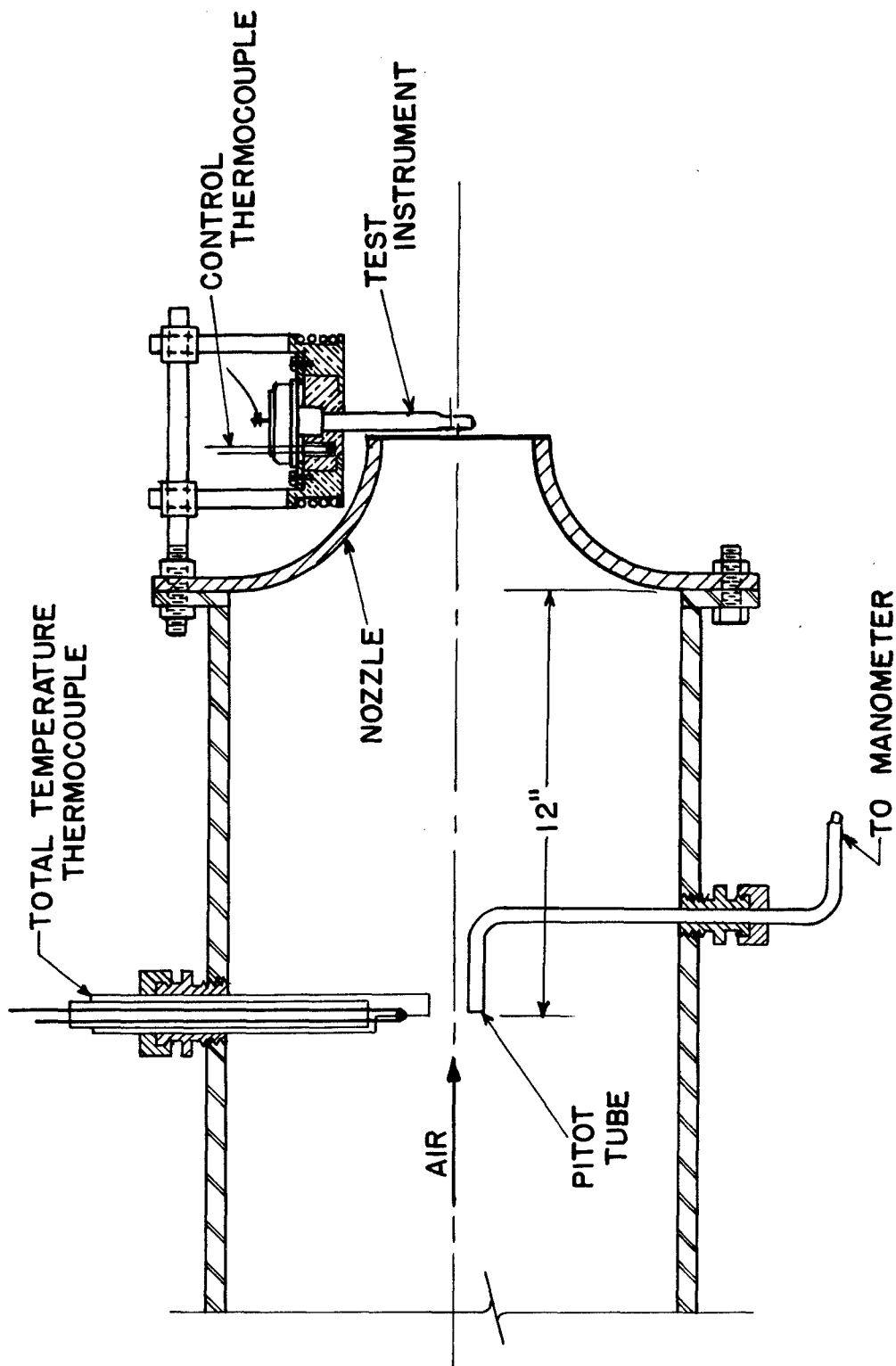


FIGURE 4 APPARATUS FOR DETERMINING RECOVERY FACTOR

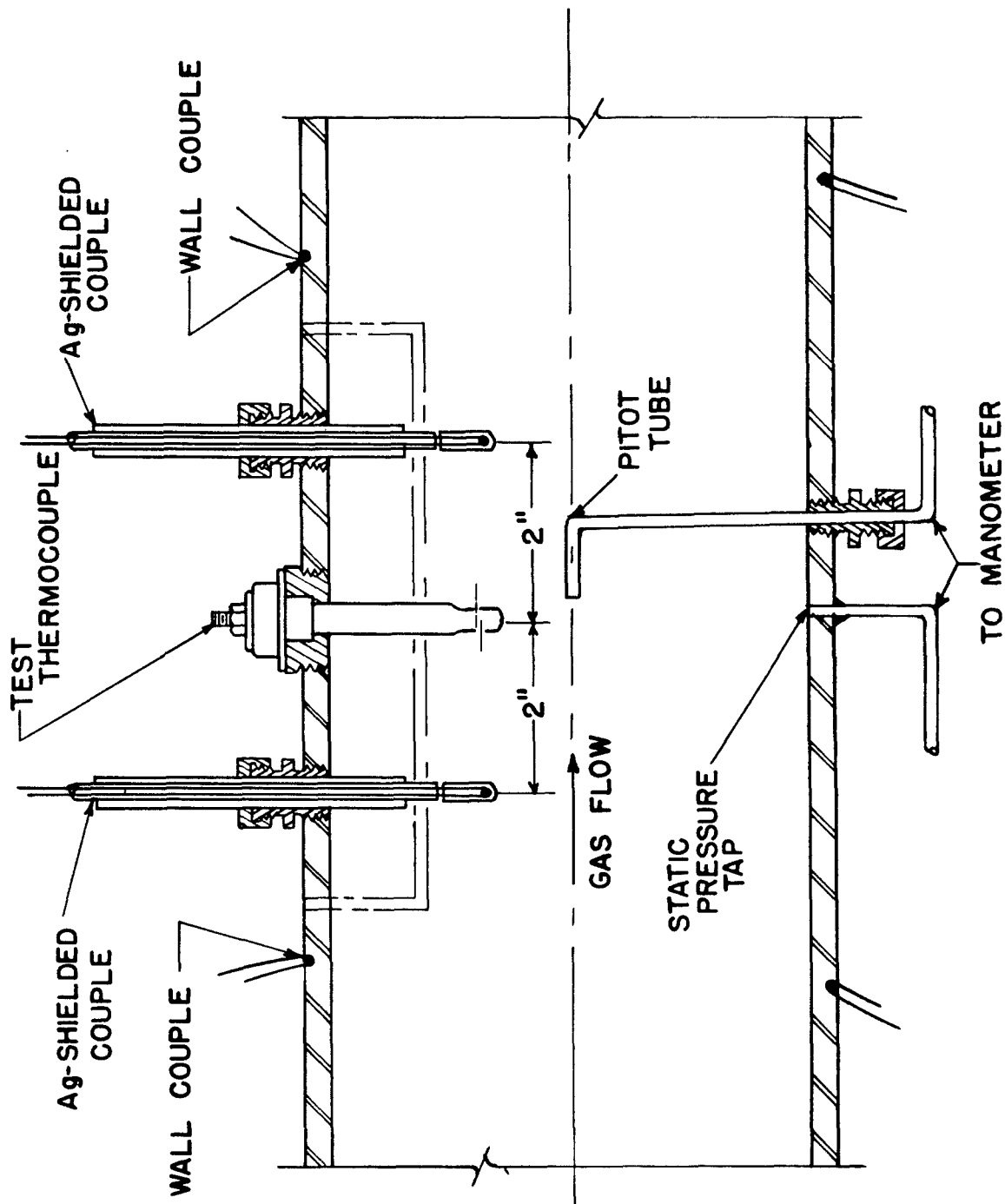


FIGURE 5 ASSEMBLY FOR CALIBRATION TESTS