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BIMETAL SENSOR FOR AVERAGING TEMPERATURE MEASUREMENT OF NONUNIFORM TEMPERATURE PROFILES

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SUMMARY

A single-probe instrument was developed for measuring an average temperature over a nonuniform temperature profile. This probe uses the principle of differential thermal expansion of two different materials. The performance of such a probe was demonstrated experimentally by using a prototype probe for a single temperature indication over temperature profiles which varied as much as 750° C. Probe temperature measurements obtained during several runs averaged as much as 13° C lower than temperatures obtained from averaging the measurements of eight thermocouples equally spaced along the probe length; analysis shows that for steep temperature gradients the probe-measured temperature is a better average than the average temperature obtained from the eight thermocouples. The instrument can be adapted to wide temperature ranges by the proper selection of probe geometry and materials.

INTRODUCTION

The usual method used to determine an average temperature for a span of nonuniform temperatures consists of averaging a series of point temperature measurements. If the span is long or contains large temperature gradients, the number and distribution of point temperature measurements affects the accuracy of the calculated average temperature. Although an increase in the number of point measurements improves accuracy, this may not always be practical because of increased equipment and data-processing effort.

A bimetal probe utilizing the principle of differential thermal expansion can be used to obtain an average temperature over a nonuniform temperature profile, provided that the resulting differential expansion is truly representative of the temperature average. Such a probe can be applied to indicate, by a single meter readout, an average temperature over a nonuniform temperature profile, for example, in jet engine ducts, heat exchangers, ovens, and furnaces. Bimetal differential elongation probes have been used as steady-state temperature indicators and for actuating temperature controllers (refs. 1 and 2); however, no study or analysis of bimetal probe performance in a nonuniform temperature field was found in the literature.

This report describes the principles of operation, design, and calibration of bimetal probes to be used to measure average temperatures across nonuniform temperature profiles. In addition, a prototype instrument was designed, built, and used to measure an average temperature across a nonuniform temperature profile under steady-state conditions. The performance of this temperature probe was evaluated by comparing the temperature indication obtained with this probe with the arithmetically averaged temperature measured by eight thermocouples.

PRINCIPLE OF OPERATION

The principle of operation of the temperature-averaging probe is an application of the expansion of a solid material caused by a change in temperature. The expansion coefficient α relates the change in length Δl of a solid material to a change in temperature $T_2 - T_1$, as follows:

$$\Delta l = l_2 - l_1 = l_1 \alpha (T_2 - T_1) \tag{1}$$

where l_1 is the material length at a reference temperature T_1 and l_2 is the material length at final temperature T_2.

Applying equation (1) to a practical temperature-measuring instrument requires two metals with substantially different thermal expansion coefficients so that the difference in elongation is large for relatively small changes in temperature. In general, such a temperature probe consists of two parallel members of dissimilar materials a and b joined together at one end so that a change in temperature along the probe length produces a difference in elongation at the free ends of the two materials. When the temperature along the probe length is nonuniform, the total difference in elongation at the free ends is a summation of local differences as generated by local temperatures along the probe. Thus, the total difference in elongation becomes a measurement of the average temperature along the length of the probe. From this elongation measured with a linear transducer system and a calibrated meter, an average temperature across the span of the probe is measured as a single readout.

The difference in elongation of the probe members a and b is related to temperature by the following equation for $l_{a,1} = l_{b,1} = l_1$ at temperature T_1

$$\Delta l_{(a - b)_2} = l_1(T_2 - T_1)(\alpha_a - \alpha_b) \qquad (2)$$

where

a, b	probe materials
l_1	length of materials a and b at temperature T_1
$\Delta l_{(a - b)_2}$	difference in elongation of materials a and b at temperature T_2
T_1	reference temperature
T_2	final temperature
α_a	mean thermal expansion coefficient of material a for temperature range T_1 to T_2
α_b	mean thermal expansion coefficient of material b for temperature range T_1 to T_2

DESIGN CONSIDERATIONS

The design of a bimetal probe to be used in a practical application should be based on the following considerations: (1) probe geometry, (2) materials, (3) indicating meter, and (4) calibration.

Probe Geometry

Basically, the bimetal probe consists of parallel members of two dissimilar materials which are joined together at one end. The free ends are attached to a meter device that measures the magnitude of the differential movement (fig. 1). For applications re-

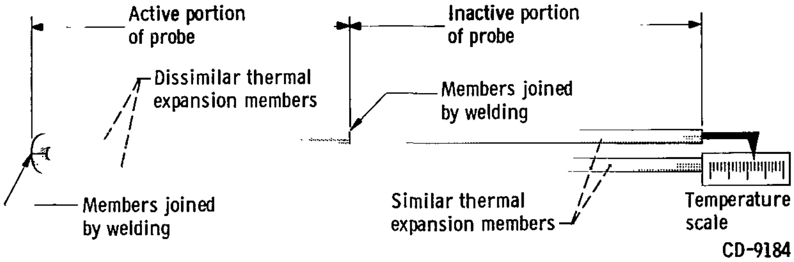


Figure 1. - Temperature probe design principle.

quiring probe immersion in liquids or in high-temperature fields, it may be necessary to isolate the meter from the temperature-measuring region. For these installations, the differential elongation of the active portion of the probe may be transmitted to the meter by an inactive extension wherein the same material is used for both members (fig. 1). Thus, within this extension, changes in temperature will change both member lengths equally but have no effect on the relative member lengths.

The parallel members of the probe may be in the shape of rods, bars, or tubes with dimensions of cross section and length depending on the requirements of the specific application. Generally, the cross-sectional dimension should be small in order to minimize probe response time with changes in temperature. However, for relatively long probes, flexibility of the parallel members increases as their cross-sectional area is reduced. This flexibility may allow the two probe members to separate, sag, or bend unevenly and thereby affect their relative lengths and result in erroneous and erratic temperature measurements and hysteresis. Long probes thus may require external supports to maintain the members parallel and straight.

Materials

The selection of the two probe materials is based on the operating temperature range, the metallurgical stability, and the mechanical strength and rigidity at the maximum working temperature. A large difference in thermal expansion coefficients is desired to obtain high sensitivity. A preliminary selection of the two probe materials may be made by comparing room-temperature expansion-coefficient values for various materials as shown in table I. The expansion coefficients of some metallic alloys vary considerably with composition. For example, the different compositions of nickel-iron alloys show a variation in expansion coefficient at room temperature from 0.9×10^{-6} to 19.5×10^{-6} centimeter per ^{o}C.

The two materials selected must expand uniformly throughout the required temperature range, that is, the expansion as a function of temperature must not exhibit inflection points, such as are caused by molecular transformation (ref. 1). The materials must also be chemically stable and compatible with the environment up to the maximum operating temperature in order to prevent corrosion, oxidation, and fluid contamination. Another consideration in the selection of the two materials is the physical strength at maximum temperature and the resistance to bending caused by the forces of gravity or the impact of high-velocity streams.

TABLE I. - THERMAL EXPANSION COEFFICIENTS FOR VARIOUS SELECTED SOLID MATERIALS AT ROOM TEMPERATURE

Material	Melting point, ^{o}C	Linear coefficient of thermal expansion, per ^{o}C	Reference
Aluminum	660	24.0 $\times 10^{-6}$	4
Brass, 66-percent copper and and 34-percent zinc	927	18.9	
Copper	1082	16.8	
Gold	1063	14.3	
Iron (wrought)	1510	11.4	
Lead	327	29.4	
Magnesium	651	26.0	
Molybdenum	2620	4.9	
Nickel	1455	12.8	
Nickel-steel alloys			
Percentage of nickel:			
10	1500	13.0	
20		19.5	
30		12.0	
36 (Invar)	1495	.84	
40		6.0	
50		9.7	
80		12.5	
Platinum	1773	9.0	
Pyrex	>700 (softens)	3.6	
Quartz (fused)	>1425 (softens)	.42	
Silver	961	18.8	
Steel	1430	12.0	
Steel, stainless (300 series)	1425	16.5	5
Steel, stainless (400 series)	1480	9.9	5
Tantalum	3000	6.7	4
Tungsten	3370	4.3	4

Indicating Meter

The linear motion produced by the probe may be indicated on a meter attached directly to the probe assembly, or the motion may be converted, by a transducer, to a signal for actuating a remote meter. Several types of transducers are available, such as the pneumatic bridge (ref. 2), the electric strain gage, or an inductive displacement transducer.

Calibration

The probe and meter assembly may be calibrated experimentally by immersion of the active portion of the probe into at least three different uniform-temperature baths such as baths at the known fixed boiling or freezing points of various liquids or baths whose temperatures are determined by previously calibrated thermocouples or thermometers. Another method is to calibrate the instrument analytically by using equation (2). However, the accuracy of the results obtained when equation (2) is used depends on the correctness of the expansion coefficients used. Often, when comparing expansion coefficients from several sources in the literature, a range of values is obtained.

PROTOTYPE INSTRUMENT

A temperature-measuring probe assembly was constructed and tested in order to evaluate prototype probe performance. The probe assembly was constructed of commercially available materials and tested at conditions up to the operating limits of existing facilities.

Materials

The materials, AISI type 316 stainless steel and tungsten, were chosen for the active portion of the bimetal probe because of their widely different thermal expansion coefficients. The variation of each mean coefficient of thermal expansion α as a function of temperature is shown in figure 2. The expansion coefficients for stainless steel were given in reference 5 as mean values for each of two different temperature ranges. These values were plotted in figure 2(a) at the maximum temperature of each range. The variation of expansion coefficient with temperature was assumed to be linear between these

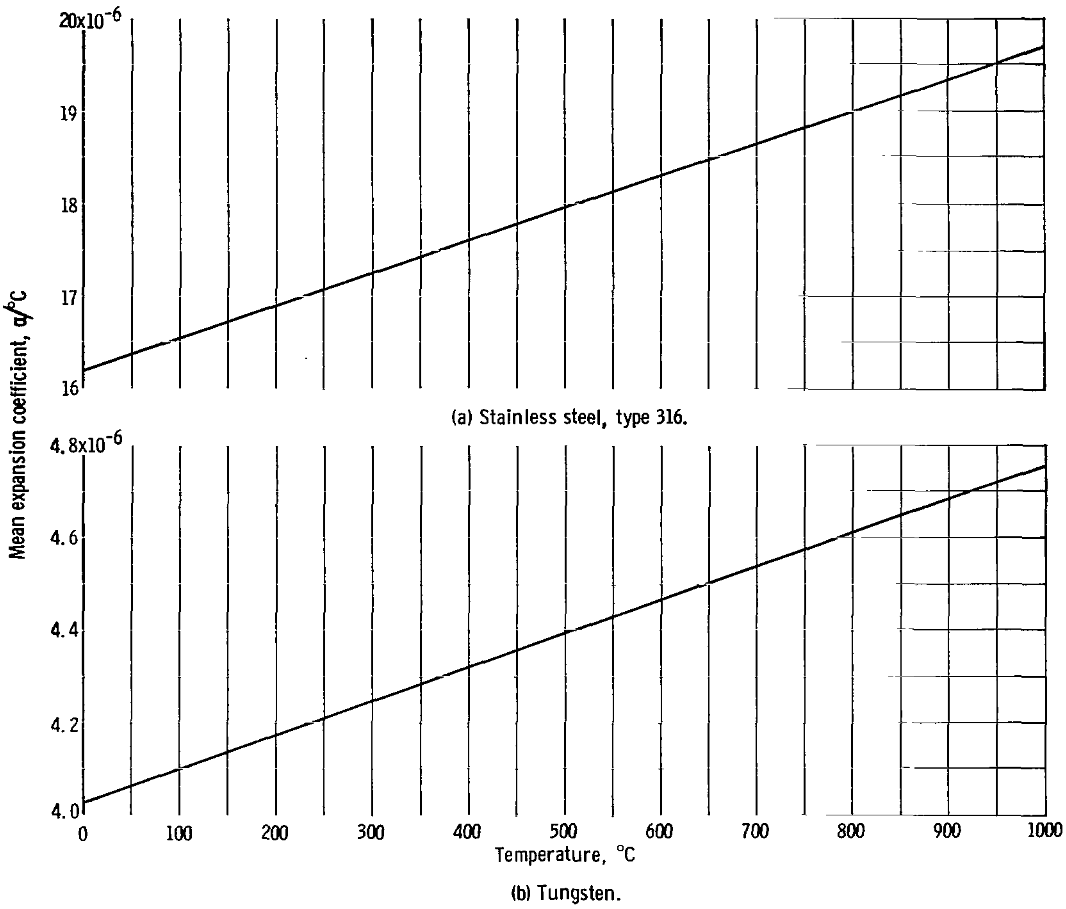


Figure 2. - Variation of mean thermal expansion coefficient with temperature.

two temperatures. The values for the mean expansion coefficient of tungsten, as a function of temperature, were obtained from reference 3 and are plotted in figure 2(b).

Design

For the prototype instrument, an active probe length of 35.6 centimeters, tested in the range from room temperature to about 800° C, was considered adequate. Both tungsten and stainless-steel rods were readily available only with a diameter of 0.157 centimeters. A probe extension consisting of 55.8-centimeter-long stainless-steel rods was used to locate the transducer at a safe distance from the heated portion of the probe. Details of the prototype probe and transducer are shown in figure 3.

Because of the flexibility of the small-diameter probe rods, two stainless-steel rods were placed parallel to and on either side of the tungsten rod in order to reduce the flexibility of the probe. Also, narrow stainless-steel bands were wrapped around the rod

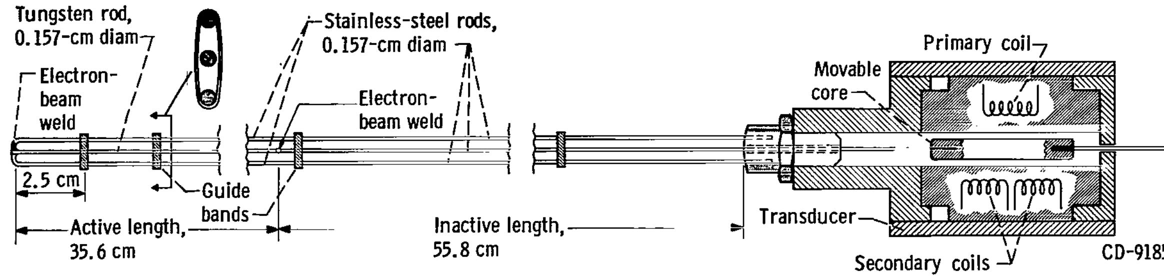


Figure 3. - Details of prototype temperature-measuring probe and transducer.

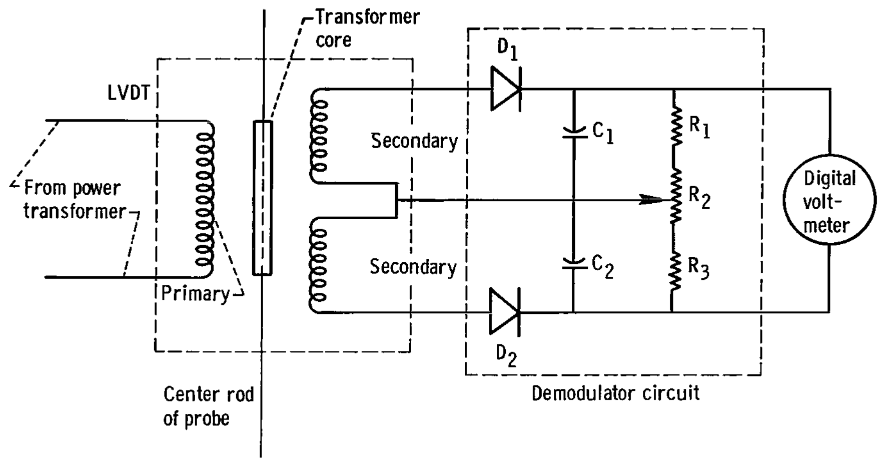


Figure 4. - Schematic drawing of differential transformer and demodulator circuits. Demodulator circuit provides direct-current voltage signal directly proportional to displacement of linear variable differential transformer (LVDT) core.

bundle at intervals of 2.5 centimeters along the entire probe length. These bands were spot welded to the stainless-steel rods only, and thus allowed free axial movement of the tungsten rod but prevented such lateral flexing as would have affected relative rod lengths.

The transducer used was a commercially available linear variable differential transformer which, together with appropriate circuitry (fig. 4), generates an output voltage that is proportional to the axial displacement of the core within the transformer. The body of the transducer was attached to the stainless-steel probe members, while the movable transformer core was attached to the extension of the tungsten member.

Calibration

The differential elongation $\Delta l_{(a - b)_2}$ of the probe (eq. (2)) is plotted as a function of temperature in figure 5. This elongation was calculated for a probe length of 35.6 centimeters at the reference temperature of 24° C by using mean expansion coefficient values obtained from figure 2. This curve (fig. 5) can be considered as the analytical calibration

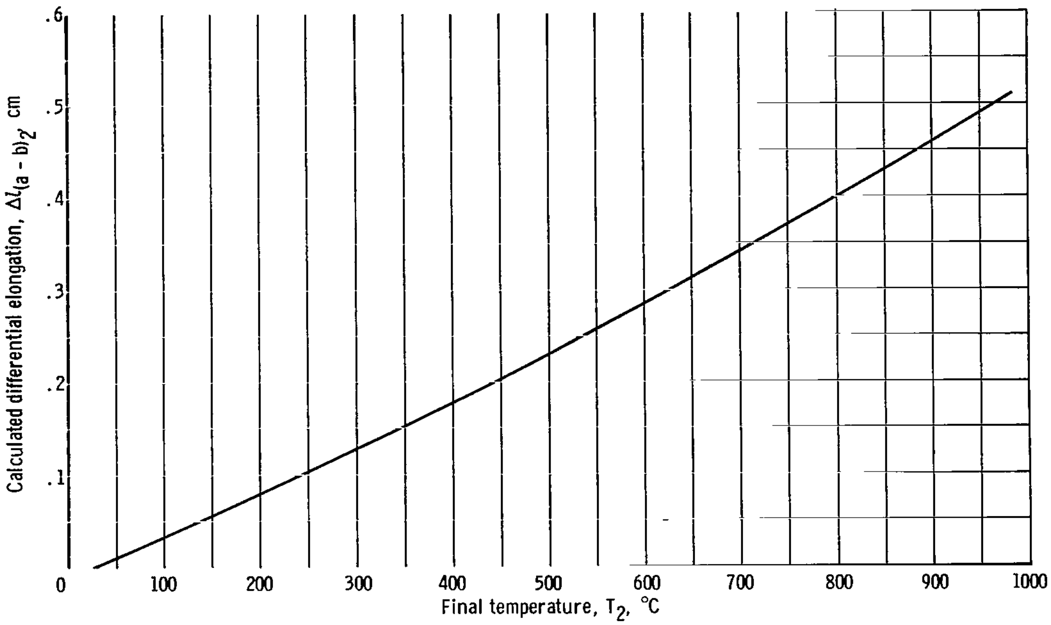


Figure 5. - Calculated differential elongation of prototype probe referenced to 24° C.

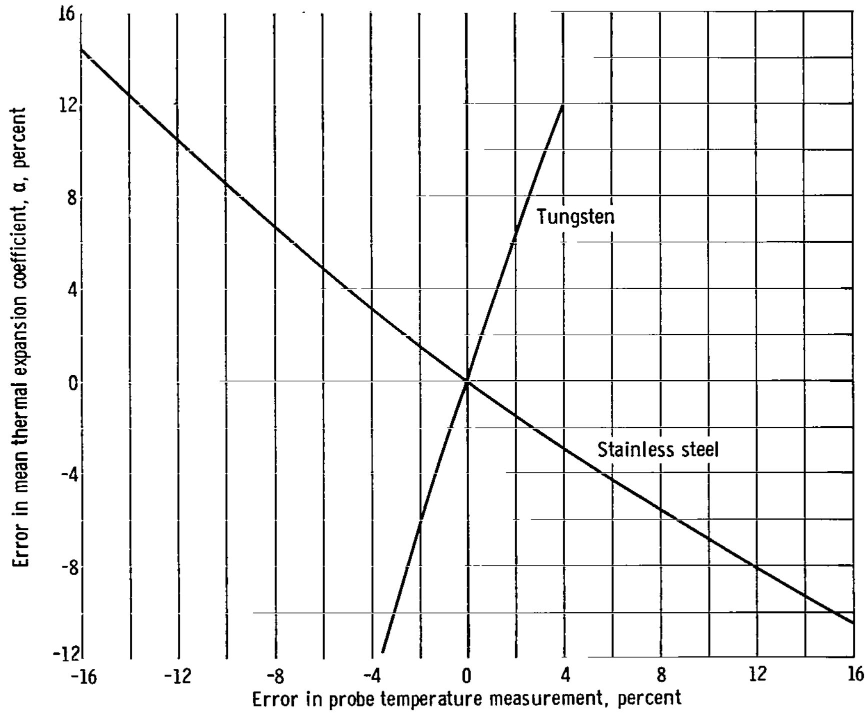


Figure 6. - Effect of percentages of error in mean thermal expansion coefficients of tungsten and stainless steel on percentage of error in probe temperature measurements.

curve for this probe. The transducer output signal was experimentally calibrated as a function of the transducer core displacement (probe elongation $\Delta l_{(a - b)_2}$). The accuracy of an analytical probe calibration, however, depends on the correctness of the mean expansion coefficient values used in the calculations. The results of a literature survey on the mean thermal expansion coefficient of tungsten, as reported in reference 3, indicates a range of values from approximately 4.5×10^{-6} to 5.5×10^{-6} per ^{o}C at 1000^{o} C. An evaluation of the error in probe temperature that is introduced by an uncertainty in the thermal expansion coefficient of both tungsten and stainless steel seemed important and is presented in figure 6. For tungsten, an error of ±5 percent in mean thermal expansion coefficient α_b would result in a temperature error of about ±1.6 percent, while an error of ±5 percent in the mean thermal expansion coefficient for stainless steel α_a would result in a temperature error of about ∓6.2 percent. Thus, for accuracy in probe temperature measurements, it is recommended that the probe assembly be calibrated experimentally by immersion in known-temperature liquid baths.

Test Procedure

Probe calibration and performance tests were conducted in a 20-kilowatt controlled-temperature furnace. The active portion of the probe was inserted to four different lengths through a hole in the furnace door. Uniform probe temperature profiles, which were used for calibration checks, were obtained with full insertion of the probe in the furnace, while nonuniform temperature profiles were obtained by inserting three-fourths, one-half, or one-fourth of the active probe length in the furnace; the remainder of the probe and the transducer were exposed to room temperature.

The signal generated by the linear variable differential transformer was read on a digital millivolt meter. The sensitivity of the transducer was 206 millivolts per millimeter of core displacement with a linearity of ±0.02 millimeter.

A series of eight reference thermocouples was distributed, at intervals of 5.1 centimeters, along the active portion of the probe in order to check probe calibration and to indicate the magnitude of temperature gradients along the probe. These thermocouples were spaced 0.5 centimeter from the probe and supported by a 0.64-centimeter-diameter tube (fig. 7) which also held the thermocouples leads. The temperatures of the Chromel-Alumel thermocouples were determined with a calibrated self-balancing potentiometer. A schematic drawing of the test setup and instrumentation layout is presented in figure 8.

For each insertion into the furnace, the transducer voltage and the temperatures of the eight reference thermocouples were recorded at each increase in furnace temperature, in steps of about 100^{o} C, from room temperature to 800^{o} C. Additional data were taken at decreasing furnace temperature in order to determine if hysteresis would occur.

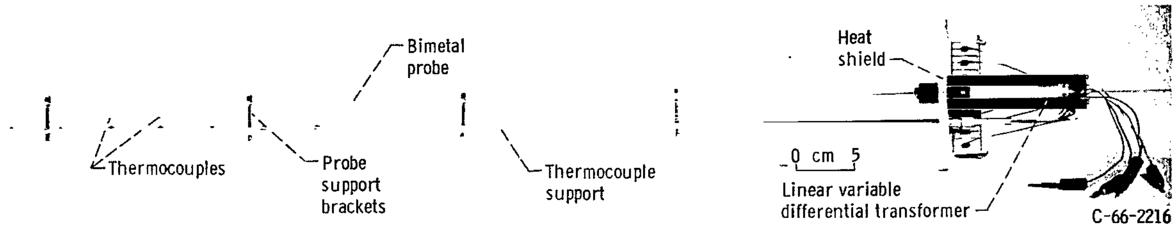


Figure 7. - Prototype temperature probe and transducer with reference thermocouples separated from probe by 0.5 centimeter.

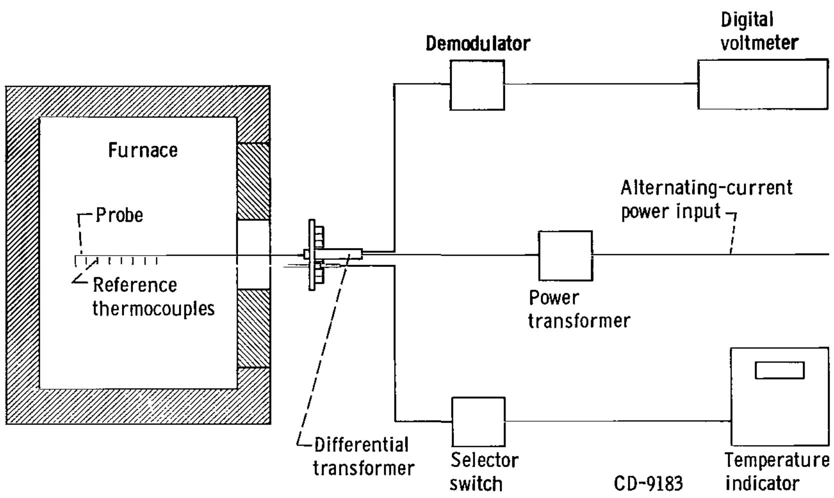


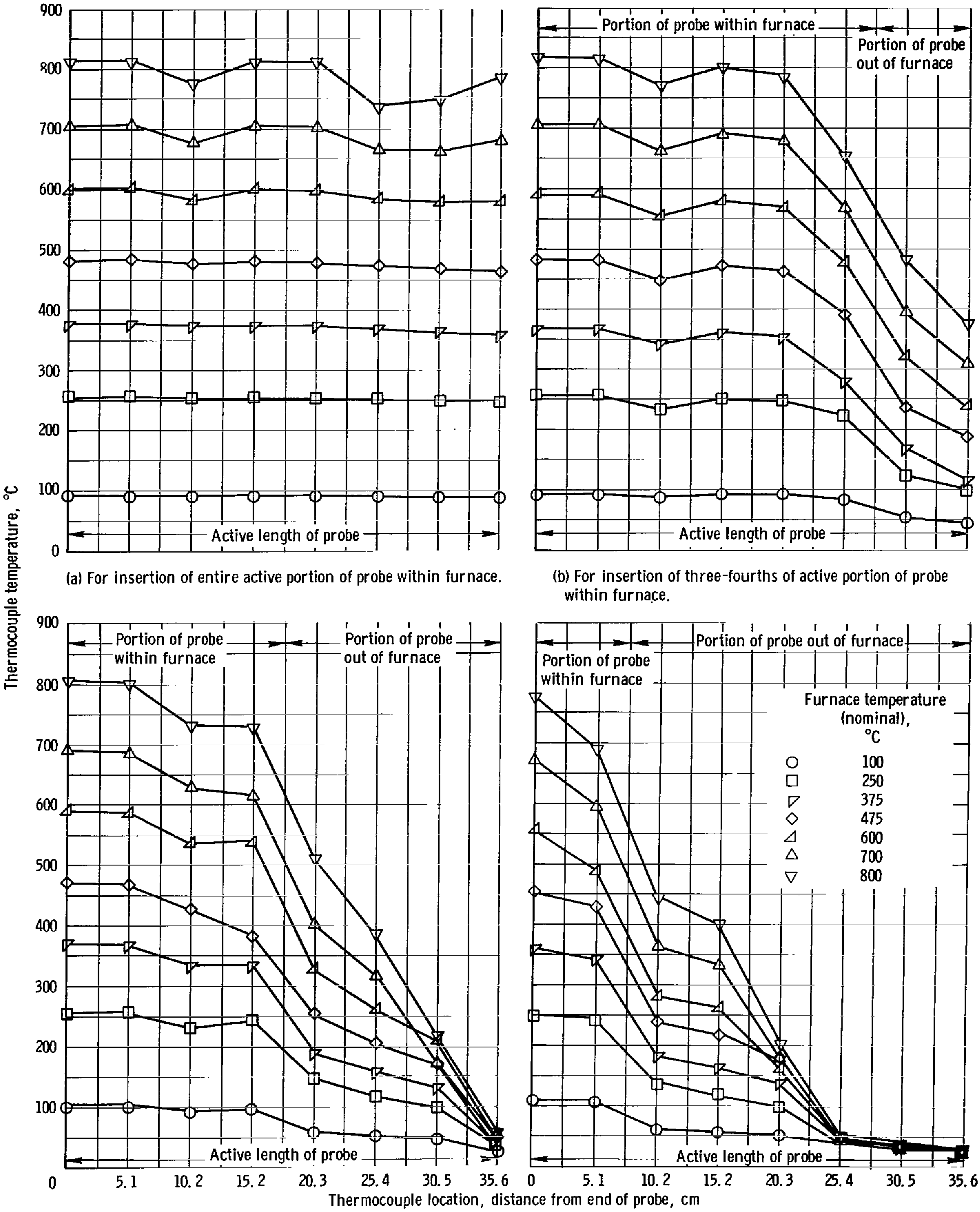
Figure 8. - Schematic diagram of instrumentation.

Although the tungsten would have oxidized if subjected for a long period of time to the higher temperatures, no difficulty was anticipated since the duration of the tests was short (of the order of 25 hr).

TEST RESULTS

Temperature Profiles

Representative probe temperature profiles obtained from the measurements with the eight reference thermocouples are shown in figure 9. The data shown were obtained at increasing furnace temperatures. Data taken at decreasing temperatures have similar temperature profiles. The maximum temperature variation along the active length of the probe for some of the tests is greater than 750° C.



(a) For insertion of entire active portion of probe within furnace.

(b) For insertion of three-fourths of active portion of probe within furnace.

(c) For insertion of one-half of active portion of probe within furnace.

(d) For insertion of one-fourth of active protion of probe within furnace.

Figure 9. - Probe temperature profiles as indicated by eight reference thermocouples.

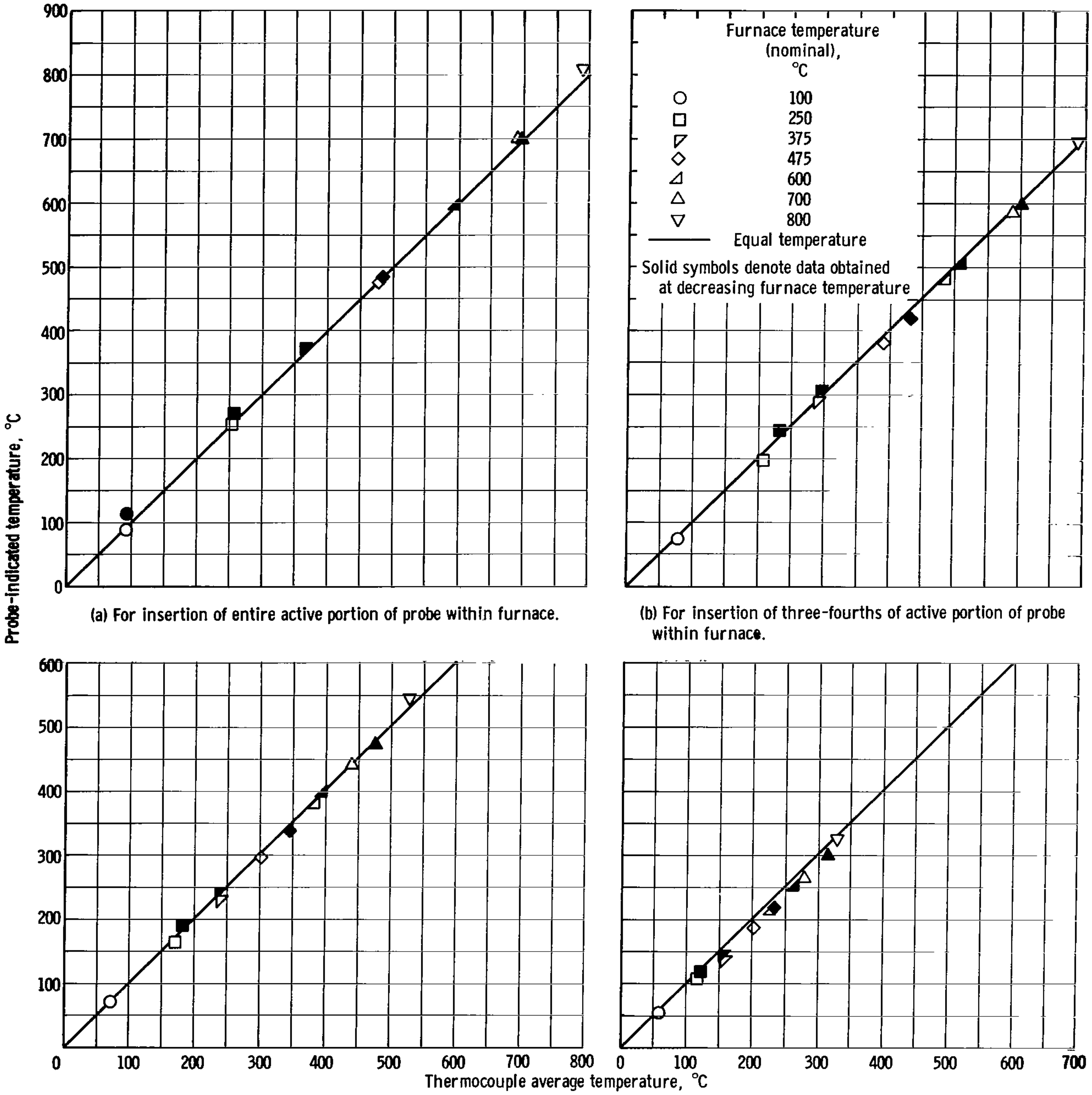
Comparison of Results

The temperatures indicated by the elongation of the bimetal probe are compared with the arithmetic average of the temperatures measured by the eight reference thermocouples for the various test conditions in figure 10. The 45° line indicates equal temperatures.

The results obtained with a uniform temperature profile are used to check the analytical probe calibration, as shown in figure 10(a). The maximum disagreement in temperature measurements is about 25° C. The probe temperatures average about 8° C higher than those obtained from the thermocouple measurements.

The average temperatures for nonuniform temperature profiles as obtained by the two measuring methods are compared in figures 10(b), (c), and (d). Agreement within 20° C is shown for all nonuniform temperature profiles tested. Some of these nonuniform temperature profiles have temperature variations along the active probe length greater than 750° C (figs. 9(c) and (d)). The calculated average temperature deviation for the data in figures 10(b) and (c) indicates the probe temperature to average about 3° C lower than the thermocouple temperature, and, for the data shown in figure 10(d), the probe temperature averages 13° C lower.

In an effort to explain the consistent temperature deviation of the temperature profile of figure 10(d), where one-fourth of the active probe length is inserted in the furnace, the thermocouple data were investigated more thoroughly. It is believed that eight thermocouples are too few to integrate over a profile 35.6 centimeters long if the temperature gradient is steep. The limited thermocouple data were extrapolated in figure 11 to obtain an average temperature for an infinite number of thermocouples. In this figure, the reciprocal of N number of thermocouples $1/N$ is plotted against an average temperature obtained from N number of thermocouples. The extrapolations of the data to $1/N = 0$ or $N = \infty$ indicate that, when the average of eight thermocouples is less than the midpoint of the extreme temperatures of the profile, an infinite number of thermocouples would give a still lower temperature (fig. 11(c)). Conversely, when the average of the eight thermocouples is greater than the midpoint of the extreme temperatures (figs. 11(a) and (b)) an infinite number of thermocouples would give a higher temperature. In applying these trends to the data of figures 10(b), (c), and (d), it seems that, for steep temperature gradients, the probe-measured temperature is a better average than the average temperature obtained from eight thermocouples.



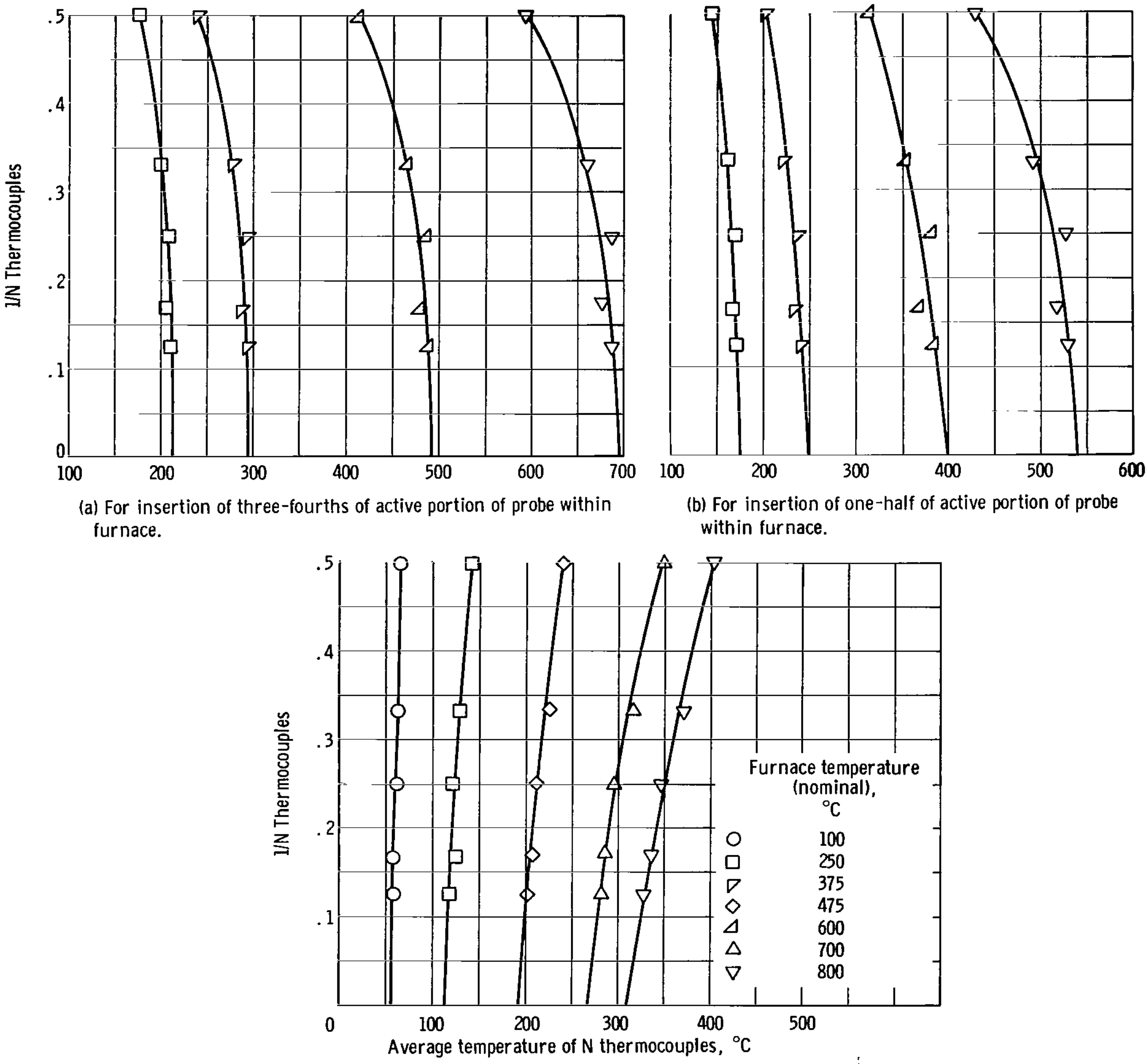
(a) For insertion of entire active portion of probe within furnace.

(b) For insertion of three-fourths of active portion of probe within furnace.

(c) For insertion of one-half of active portion of probe within furnace.

(d) For insertion of one-fourth of active portion of probe within furnace.

Figure 10. - Comparison of bimetal-probe indicated temperature with thermocouple average temperature. Each symbol identifies a temperature profile shown in figure 9 and a temperature average shown in figure 11.



(a) For insertion of three-fourths of active portion of probe within furnace.

(b) For insertion of one-half of active portion of probe within furnace.

(c) For insertion of one-fourth of active portion of probe within furnace.

Figure 11. - Average temperatures of N number of thermocouples extrapolated to 1/N = 0.

CONCLUSIONS

The temperatures indicated by a prototype 35.6-centimeter-long bimetal probe were compared with the arithmetic average of temperatures obtained from eight reference thermocouples spaced equally along the probe at test conditions which indicated temperature profiles that varied as much as 750° C.

For the nonuniform temperature profiles, the bimetal probe averaged as much as 13° C lower than the arithmetic average temperature obtained from the eight reference thermocouples. An analysis shows that for steep temperature gradients the bimetal probe measured temperature is a better average than the average temperature obtained from eight thermocouples.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, July 11, 1967,
701-04-00-02-22.

REFERENCES

1. Hidnert, Peter; and Souper, Wilmer: Thermal Expansion of Solids. Optics, Metrology, and Radiation. Vol. 3 of Precision Measurement and Calibration. Handbook 77, vol. 3, National Bureau of Standards, Feb. 1, 1961, pp. 349/1-380/29.
2. Zabel, Patrick H.: Temperature Control and Measurement by a Pneumatic Bridge. Applied Methods and Instruments. Vol. III, Part 2 of Temperature, Its Measurement and Control in Science and Industry, American Inst. of Physics, 1962, pp. 823-835.
3. Tietz, T. E.; and Wilson, J. W.: Behavior and Properties of Refractory Metals. Stanford Univ. Press, 1965, p. 325.
4. Anon.: Handbook of Chemistry and Physics. 41st ed. Chemical Rubber Publishing Co., 1959, pp. 2322, 3235.
5. Anon.: Stainless Steel Handbook, Allegheny Ludlum Steel Corp., Pittsburgh, Pa., 1959.

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