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DESIGN AND CONSTRUCTION OF NEEDLE THERMOCOUPLES.

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I. INTRODUCTION

Thermocouples have been widely used to measure and record the temperatures of various components of complex heated systems. However, certain difficulties often arise in attempts to use standard two-wire thermocouples in these applications. Such couples require that the two wires be insulated from each other except at the sensing tip and that the assembly be enclosed in an impervious metal or ceramic protection tube. Such couples are bulky, somewhat fragile and inflexible, difficult to insert into a confined space, and difficult to bring out through a tortuous path.

Many of these difficulties could be overcome by a rod and tube type of construction. These needle thermocouples consist of an insulated wire of one couple component inserted into a tube of the second component, the hot junction between rod and tube being formed by welding. Such couples can be made quite small in diameter by using hypodermic needle tubing and fine wire inserts; the insulation is held in place by the tube itself and the tube can serve as its own protection. Such couples are quite flexible and can be threaded thru small and winding passageways.

Since the tube component of the couple serves as its own protection tube, the material should be resistant to attack or deterioration by the environment in which it is to be used. However, not all materials which satisfy this requirement can be obtained in the form of small diameter hypodermic needle tubing. The insulation must be of such nature that it can be applied to a fine wire, should be flexible, and should be resistant to thermal, mechanical, and other types of damage. The couple combination should have large thermoelectric power, small mass and low heat capacity to sense temperature changes. The couple should have good reproducibility of electromotive force upon repeated heating and cooling and should be resistant to mechanical damage by thermal cycling. To achieve this aim a group of material combinations has been studied; a suitable technique for the assembly of the couple components has also been investigated.

II. PRINCIPALS OF DESIGN AND ASSEMBLY

The construction of a thermocouple for the applications discussed above consists mainly of inserting an insulated wire into a small diameter tube of the hypodermic needle type and drawing (sinking) the tube through a die on a drawbench, thereby tightly gripping and sealing the wire within the

tube. In some instances needle tubing of certain materials was available in small enough diameters to allow the drawbench operation to be discarded; the drawing operation always carried the hazard of injury to the insulation by pinching it too tightly between wire and tube. The tube and wire, being of dissimilar material, comprise the couple components. A hot junction is obtained by fusion of the wire and tubing at one end; another function of fusion is to seal off one end of the thermocouple.

The primary intention was to utilize commercially available materials throughout, with strong consideration being given to selection of tube materials resistant to attack by air and alkali metals. Nickel, stainless steel and inconel tubing, having good corrosion resistance and being readily available, have served principally as stock material. Different wire materials and electrical insulations were "fitted" in various combinations to these types of tubing.

Different wire insulations were tested for their ability to resist deterioration at 600°C. Baked-on paint enamel coatings, applied on copper and constantan wire, were the least durable, showing rapid decay when temperature was raised above 250°C. Single glass fiber insulations were acceptable up to 500°C, with signs of deterioration at this temperature. Double spun glass fiber insulation, impregnated with a silicone resin, has proven satisfactory for use at temperatures up to 600°C. A five cycle heating - cooling test of a constantan wire thus treated, extending over two weeks, left the insulation intact and exhibited no signs of deterioration. Triple layers of spun glass insulation showed no marked improvement in appearance after repeated heating to 600°C; in addition, this material was not readily available at the time of this investigation. Of especial note is "Vitrotex," an insulating material for application only on copper wire; this product of the Anaconda Wire and Cable Company is essentially a multiple glass fiber wrapping, coated with a silicone enamel binder, and heat treated. Its plasticity was remarkably good after repeated heating cycles to 600°C. The thermocouples were individually calibrated against a standard chromel-alumel couple and subjected to repeated heating and cooling cycles.

The thermocouples, described in the following text, consists of needle tubing of selected materials ranging in size from 0.040" - 0.090" outside diameter with an inside diameter of 0.020" or larger. A small diameter wire corresponding to No. 30 gauge (approximately 0.015" including insulation) was selected to permit the assembly of long lengths.

III. CALIBRATION AND TESTING

The various couples constructed during this study were calibrated against a standard chromel-alumel couple using the apparatus shown in Figure 1. The hot junctions of the standard couple and the needle couples were placed close together in a tube furnace. Simultaneous measurement of couple potentials were made on separate potentiometers. The reference junction (not shown on Figure 1) was an ice bath at 0°C.

IV. RESULTS

The following needle thermocouples were constructed, calibrated, and evaluated. In the descriptions of these couples, the tube material is listed first, the wire material second.

1. Stainless Steel-Aluminum: A stainless steel-aluminum couple was considered at first, using a 0.030" 2S aluminum wire as insert. The wire was anodized to a depth of 0.003" - 0.006" to produce a nonconducting insulation against the stainless steel tubing. This coating method has not proven satisfactory; the poor adhesion of the anodized layer is aggravated by severe abrasion when a long length of wire is inserted and pulled through the tubing. Short circuiting occurred during several of these assembly attempts even before calibration.

2. Stainless Steel-Copper: Type 316 stainless steel tubing (0.084" O.D., 0.030" I.D., 9 feet long) was used in conjunction with "Vitrotex" covered copper wire. This thermocouple assembly was not drawn down. The calibration of this type of couple exhibited the lowest thermoelectric power of the examined series. The internal resistance was 35 - 37 ohms. The calibration data are given in Table I and plotted in Figure 2.

3. Inconel-Copper: Inconel Tubing, (0.073" O.D., 10 feet long) was used in combination with a copper wire insulated with "Vitrotex." The tubing with the inserted wire was swaged down at one end to provide an adequate point to start a drawing operation. One single draw, to 0.064" O.D., was made using a standard tungsten carbide wire die and colloidal graphite as lubricant. The emf generated with this material combination is very low and of erratic response in re-calibration. Internal resistance of the thermocouple was approximately 40 ohms. The calibration data are given in Table I and plotted in Figure 2.

4. Kovar-Copper: The above material combination was investigated using Kovar tubing (54% iron, 28% nickel, 18% cobalt) (0.040" O.D., 0.009" wall thickness). The wire insert consisted of "Vitrotex" coated copper wire, No. 30 gauge. The tube assembly was put through a sizing die to alleviate coiling tendency of this thin 12 foot long tubing. Internal resistance of the couple after calibration was 46 ohms. A bowed calibration curve and relatively low emf was obtained for this couple combination. Calibration data are given in Table I and plotted in Figure 2.

5. Kovar-Constantan: The same tubing material and size as above was used, inserting a No. 30 gauge wire of constantan (an alloy of approximately 60% copper, 40% nickel). The wire insulation consisted of a double layer of spun glass and a silicone oil treated wrapping. Drawbench facilities were utilized here also to combat coiling of the thin 12 foot long tubing. Calibration was undertaken up to 635°C and two heating-cooling cycles were applied. Internal resistance was 40 - 45 ohms. Calibration data are given in Table I and plotted in Figure 2.

6. Nickel-Constantan: Grade A nickel tubing, (8-1/2' long, 0.090" O.D. and 0.020" wall thickness) was used in conjunction with No. 30 gauge constantan wire insulated as mentioned above. This tube assembly was drawn down in succession through 0.078", 0.068", 0.058" and 0.048" dies at a speed of about 12 inches per minute. Colloidal graphite served as lubricant. Direct reduction, as attempted through the final 0.048" die, left the assembly twisted and impossible to straighten. This thermocouple generated only a relatively low thermoelectric force at 600°C. Internal resistance of the couple was approximately 40 ohms. Calibration data are given in Table I and plotted in Figure 3.

7. Nickel-Copper: Grade A nickel tubing (0.074" O.D. by 0.020" wall thickness) was used in conjunction with "Vitrotex" insulated No. 30 gauge copper wire. A ten foot long thermocouple was assembled and calibrated. The needle couple prior to calibration was pulled through a sizing die to prevent twisting. The generated emf was nearly proportional to temperature, and the couple held its calibration during several heating and cooling cycles. Calibration data are given in Table I and plotted in Figure 3. Internal resistance measured 45-48 ohms.

8. Nickel-Chromel: To investigate the emf properties of chromel versus nickel, a thermocouple was constructed using wire for each of the components instead of the tubing/wire type of design. This was necessary due to the inadequate insulation of the chromel wire, making it unsuitable for direct insertion into the nickel tubing. The wires were therefore separated in the conventional manner by silimanite beads. The emf generated was satisfactorily reproducible and was slightly higher than that of the standard chromel-alumel thermocouple. The calibration data are given in Table I and plotted in Figure 3.

9. Copper-Constantan: Hypodermic needle type copper tubing, O.F.H.C., into which was inserted a No. 30 gauge constantan wire, double layer spun glass insulated, was used. The tube assembly was eight feet in length. The outside diameter of the copper tubing (0.090") was reduced prior to wire insertion in one pass through a 0.058" wire die without encountering the curling effect observed in other tubing, notably nickel. Calibration was made up to 610°C and subjected to two heating-cooling cycles. The tubing tarnished badly at higher temperatures, giving an erratic emf. The calibration data are given in Table I and plotted in Figure 3.

10. Inconel-Constantan: In attempts to develop a needle thermocouple with higher than average electromotive power, inconel versus constantan has proven a most desirable choice. Not only was a high emf (36.59 mv at 600°C, versus 24.97 mv at 600°C for a chromel-alumel couple) produced, but the reading was consistently reproducible for six consecutive heating-cooling cycles. Calibration was performed against a chromel-alumel thermocouple for temperatures up to 600°C. These data are given in Table I and plotted in Figure 3.

The construction and assembly procedure remained essentially identical with the other thermocouples investigated. 10 - 12 feet random length inconel tubing, 0.076" O.D., 0.014" wall thickness, was used. The wire insert consisted of No. 30 gauge constantan wire insulated with double or triple layers of spun glass and silicone treated wrapping materials.

For extension leads to remote instruments, inconel wire was selected and was soldered to the inconel tubing assembly. This avoided extraneous emf at the reference junction and limited otherwise necessary compensations within the circuit. The internal resistance of this type of couple plus lead wires was 68 - 70 ohms.

Since this couple has a rather large thermoelectric power, the possibility of its use for measurements at moderately low temperatures was investigated. Four inconel-constantan thermocouples were constructed and calibrated in pairs against a full-immersion type mercury thermometer in the range 10° - 70°C . An oil bath equipped with an immersion heater and stirrer was used to achieve calibration of these couples. Two potentiometers coupled to prism galvanometers were used to measure the potential of the couples. The calibration data for these four couples are given in Table II and plotted in Figure 4.

V. SUMMARY

Thermocouples of very small cross section can be successfully constructed essentially utilizing a hypodermic tubing and wire design. The choice of the component materials is dependent on environment and availability of small diameter tubing. The central wire can be satisfactorily insulated from the tube with silicone resin impregnated double and triple layers of spun glass. Satisfactory couples consisting of an insulated constantan wire enclosed in an inconel tube were constructed and calibrated. These couples have a high thermoelectric power and hold their calibration well at temperatures up to 600°C .

Table I

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CALIBRATION DATA FOR NEEDLE THERMOCOUPLES. (REFERENCE JUNCTION - 0°C)

Reference Couple Chromel-Alumel + -	Temp. (°C)	Stainless-Cu* - +	Inconel-Cu* + -	Kovar-Cu* - +	Kovar-Constantan* - +	Ni-Constantan* + -	Ni-Cu* - +	Ni-Chromel* - +	Cu-Constantan* + -	Inconel-Constantan* + -
1.035	25	---	---	1.015	0.050	0.435	0.528	1.020	0.962	---
1.132	28	0.068	0.168	---	---	---	---	---	---	1.235
1.626	40	---	---	1.600	0.040	0.695	0.850	1.650	1.565	---
2.396	59	0.155	0.395	---	---	---	---	---	---	2.694
3.785	92	---	---	2.965	0.695	1.650	2.030	3.860	3.620	---
4.090	100	0.286	0.687	---	---	---	---	---	---	4.695
7.775	190	0.665	1.300	---	---	---	---	---	---	9.727
9.398	232	---	---	6.906	3.485	4.705	5.692	10.435	10.310	---
11.380	279	1.135	1.974	---	---	---	---	---	---	15.065
12.825	314	---	---	8.760	6.085	7.030	7.888	14.256	14.785	---
16.195	395	---	---	10.250	9.255	9.930	9.624	17.555	19.440	---
16.455	401	1.865	2.850	---	---	---	---	---	---	22.85
20.380	493	2.520	3.490	---	---	---	---	---	---	29.90
20.760	503	---	---	11.760	14.205	14.085	12.250	21.755	25.960	---
24.975	601	3.375	4.225	---	---	---	---	---	---	36.590
25.335	610	---	---	12.850	19.910	18.095	14.760	26.100	32.770	---
26.350	634	3.635	4.410	---	---	---	---	---	---	38.855

*emf (Millivolts)

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Table II
CALIBRATION DATA FOR FOUR INCONEL-CONSTANTAN
THERMOCOUPLES (Calibrated up to 70°C)

Temp. (°C)	Couple #1 Millivolts	Couple #2 Millivolts	Couple #3 Millivolts	Couple #4 Millivolts
9.5	-	-	0.411	0.404
10.0	0.438	0.423	-	-
15.5	0.670	0.646	0.662	0.640
20.5	0.904	0.893	-	-
20.6	-	-	0.879	0.894
24.4	1.077	1.066	-	-
24.5	-	-	1.062	1.070
30.0	1.338	1.330	1.324	1.323
35.0	1.574	1.546	1.570	1.562
39.2	-	-	1.755	1.741
39.5	1.786	1.764	-	-
43.9	1.975	1.965	-	-
44.4	-	-	1.990	1.989
48.0	-	-	2.182	2.155
48.3	2.182	2.186	-	-
55.5	2.545	2.520	-	-
56.0	-	-	2.577	2.547
59.0	-	-	2.743	2.720
59.4	2.742	2.762	-	-
70.3	-	-	3.317	3.304
70.5	3.325	3.297	-	-
Internal Re- sistance (Ther- mocouple plus lead wires)	70Ω	65Ω	70Ω	72Ω

(Inconel +, electrical resistivity at 20°C-98.1μΩ-cm; spec. resist.
590.0Ω/cir.mil.ft.)

(Constantan -, electrical resistivity 20°C-49.3μΩ-cm; spec. resist.
294.0Ω/cir.mil.ft.)

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Figure 1. Apparatus for Obtaining EMF versus Temperature for Needle Thermocouples.

Figure 2. Calibration Curves of Thermocouple Materials vs. Chromel-Alumel.
(Reference Junction 0°C)

Figure 3. Calibration Curves of Thermocouple Materials vs. Chromel-Alumel. (Reference Junction 0°C).

Figure 4. Calibration Curve for Inconel-Constantan Thermocouple for Low Temperatures (70°C approximately).