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SUBJECT: Error Analysis for In-Pile Measurement of UO_2 Fuel Temperature at 2200°C

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ABSTRACT

An error analysis for the in-pile measurement of UO_2 fuel temperature at 2200°C was carried out to determine the accuracy of a future experiment in the Materials Test Reactor (MTR) at Idaho Falls.

The main source of error was the change in the temperature profile in the fuel capsule, due to the introduction of the thermocouple probe. Preliminary calculations on a digital computer indicate that this error will be several hundred C°.

Out-of-pile experiments with beryllia- and thoria-insulated W/W25Re thermocouples were conducted. Up to the maximum temperature attained of 2300°C, beryllia proved to be a better electrical insulator. Use of beryllia led to negligibly small errors, whereas use of thoria insulator led to significant errors in the measured emf above 1800°C due to the decrease of electrical resistivity of thoria at these temperatures.

Minor effects in a gas tight seal, which the thermocouple wires go through, and those in the lead wires were also taken into consideration.

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1. SUMMARY

The accuracy of in-pile measurement of the temperature at the center of a UO_2 fuel pin up to 2200°C was evaluated. The measurements are to be carried out in the near future in the Materials Test Reactor (MTR) at Idaho Falls. A UO_2 fuel pin containing three instrumented capsules will be used. The temperature will be monitored in each capsule with an insulated W/W25Re thermocouple.

The present work is an analysis of the different sources of error expected in these experiments. The most significant error is caused by the alteration of the temperature distribution in the fuel capsule due to the introduction of the thermocouple. If the center line of fuel in the capsule is at 2315°C, the hot junction of the thermocouple will be at about 1870°C. This temperature was estimated by A.F. Zulliger using the MAMU computer program, which considers only radial heat transfer. To improve estimates of the error, a calculation including both radial and axial heat transfer with the SIFT-TOSS computer program was attempted, but recent changes in the design of the capsule made the results no longer representative of the actual phenomena. Although convergence problems were encountered in the computer solution, these calculations suggest a difference of about 200C° between centerline and hot junction. Work on a SIFT-TOSS calculation should be continued when the final decision on design is made. Though this calculated error is large, a lower temperature in the zone surrounding the thermocouple favors improved performance of the electric insulator.

Errors introduced by electric insulators were investigated. An out-of-pile calibration showed that beryllia (BeO) gives better results than thoria (ThO_2) up to the maximum temperature reached of 2300°C. Calibration curves for W/W25Re bare wire thermocouples can be used for beryllia insulated W/W25Re thermocouples. The agreement shown experimentally between the two is within $\pm$ 1%, accuracy expected for commercially available W/W25Re bare wire thermocouples. Electric shunting effects were observed in thoria beginning at 1800°C. No electric shunting was noticeable in beryllia insulator.

The hot junction of the thermocouple, made by welding with an electron-beam, was found to be very fragile. Mechanical junctions with a double knot appeared to give a very satisfactory result; the oxides of tungsten are volatile, so that oxidation did not affect the electrical contact.

The instrumented fuel capsule has a gas tight silver seal which the thermocouple wires go through. The presence of different metals in contact in a temperature gradient introduces an error. If the temperature difference remains small, this error can be neglected. For 10C° temperature difference between the ends of the seal, the correction is +5C° in the temperature of the fuel.

Copper-alloy lead wires commonly used for Pt/Pt-Rh thermocouples were tested. With a hot junction at 120°F and a cold junction at 0°C, a correction of -0.166 mv has to be made on the reading.

The possible errors caused by transmutation of the thermocouple elements depend on the duration of the experiment. This problem has been studied before and the corrections are readily available from the literature.

2. INTRODUCTION

In measuring high temperatures where optical pyrometry is not feasible, thermocouples are the most widely used temperature sensors. Their simple construction and small size allow remote operation. Unfortunately the availability of suitable construction materials restricts the choice of thermocouples when operation in a radioactive environment is necessary. Chemical and metallurgical stability and compatibility at high temperatures are essential material properties to assure satisfactory thermocouple performance. The possibility of transmutation in a neutron flux must also be taken into account when selecting thermocouple elements (1). Sensing wires and insulators with high electrical resistivity are also very important for high temperature measurements.

Plans have been made to measure UO_2 fuel temperatures in the Materials Test Reactor (MTR) at Idaho Falls. These measurements are intended to investigate the behavior of fuel and fission products at temperatures up to 2200°C. The project is being coordinated by G.W. Parker, from the Reactor Chemistry Division at ORNL.

The experiments will involve placing a UO_2 (1.5% enrichment) fuel pin from the Dresden Reactor and a similar pin containing three instrumented capsules in the A-39 core piece of the MTR (see Fig. 1). The neutron flux at this location is of the order of 1×10^{14} nv. Tungsten-rhenium alloy thermocouples will be used to monitor the fuel temperature inside the capsule shown in Fig. 2. The insulators suggested for this case are beryllia (BeO) and thoria (ThO_2). The instrumented capsules were designed by A.F. Zulliger of the General Engineering Division at ORNL.

The purpose of the work reported here was to evaluate the overall accuracy that can be expected when the experiments mentioned above are conducted sometime in the near future. The sources of error investigated can be grouped as follows:

1) Variation in the temperature distribution in the capsule due to the introduction of the thermocouple probe. This was calculated numerically.

2) Deviations caused by the varying resistivity of insulators. These were determined by calibration of BeO and ThO_2 insulated W/W25Re thermocouples against bare wire thermocouples and pyrometer.

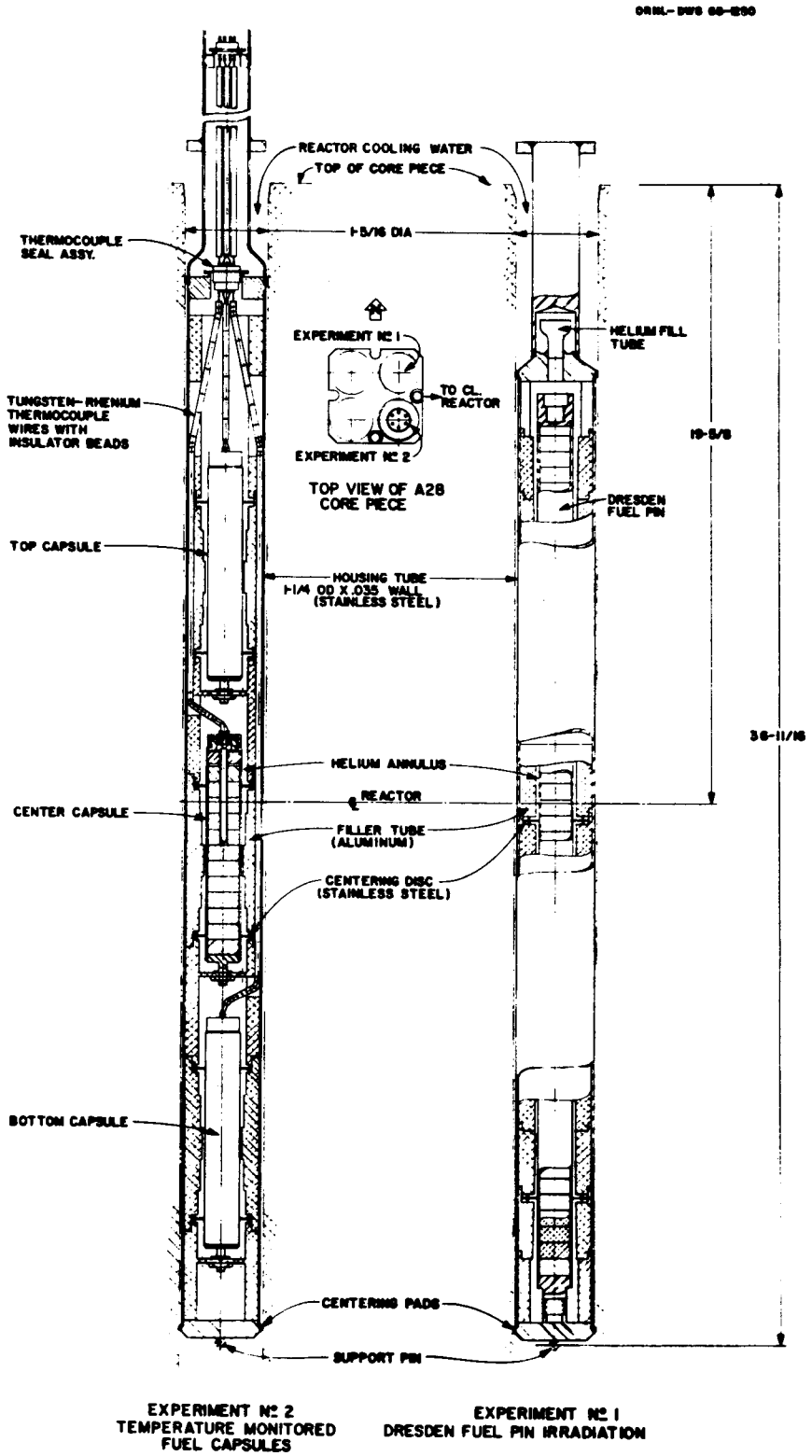

Fig. 1. Experimental Fuel Capsules

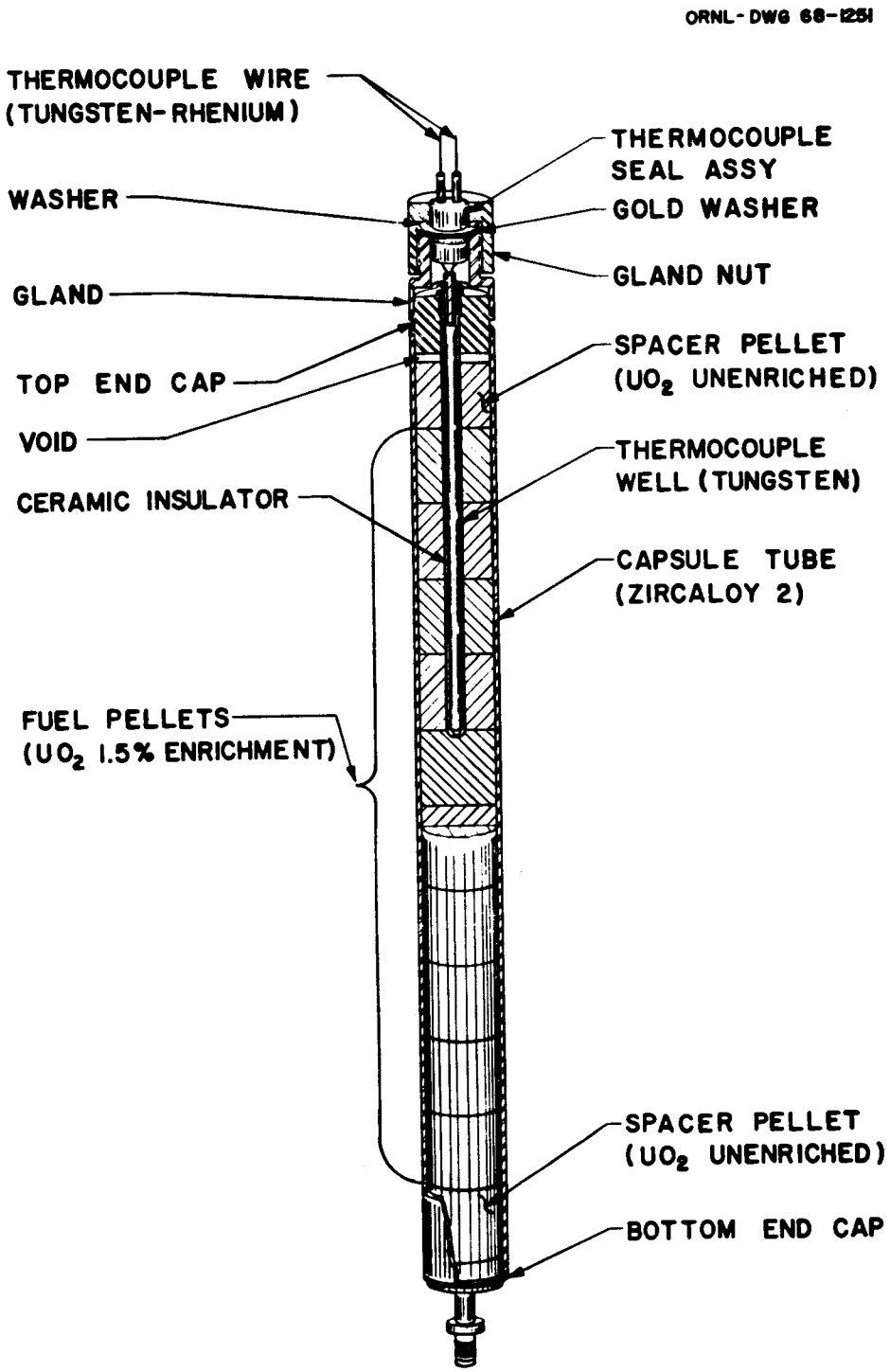

Fig. 2. Instrumented Capsule

3) Thermoelectric effects in the seal (which the thermocouple wires go through) of the capsule and in the extension lead junctions. These effects were determined experimentally.

The error caused by transmutation has been studied before by W.E. Browning and C.E. Miller (2) and the results are readily available in the literature.

Tungsten-rhenium thermocouples are currently used for temperature measurements above 2000°C, and calibration curves are available from the manufacturers. Beryllia has been observed to give satisfactory performance as an insulator, but its low melting point (2550°C) limits its applicability. On the other hand thoria has a very high melting point (3300°C), but it has reduced electrical resistivity above 2000°C. Some authors report that this reduced resistivity appears at even lower temperatures (3). Electrical shunting effects should be expected with thoria insulators. The resistivity of the insulators depends on the manufacturing process and the state of aggregation. For example, vitrified thoria is reported to give much better performance than sintered thoria (4). The size of the grain and the sintering temperature are two important factors affecting the insulating properties. In our case, fine grain thoria sintered at 3200°F was used. Data for electrical resistivity of thoria are very scarce and they disagreed from one source to another by several orders of magnitude (3, 5, 6, 7, 8) especially at high temperatures. An analytical approach to determine deviations due to electrical shunting (5) was, therefore, not appropriate in this case. Besides, the points of contact between the thermocouple wires and the insulators could vary in number during the measurements, thus introducing a randomness factor, making it difficult or impossible to calculate contact resistances.

3. ANALYTICAL PROCEDURE: DETERMINATION OF THE TEMPERATURE PROFILE IN THE INSTRUMENTED CAPSULE

It was of primary importance to have a clear understanding of the significance of the temperature read out in the instrument. To introduce the thermocouple, the amount of fuel present was reduced, and consequently the rate of heat generation was smaller in the upper part of the capsule. Furthermore, the mechanism of heat transfer was altered. Axial heat conduction through the sheath, the wires and the insulator takes place, cooling the spot that is being monitored so that consideration of radial heat transfer alone is not adequate to describe and interpret the actual phenomena. Gamma heating effects also occur in the thermocouple materials introducing minor variations in the temperature of the zone surrounding the hot junction.

It was not feasible to determine all these effects experimentally, therefore an analytical approach was necessary. Digital computation simplified somewhat the solution of the problem. SIFT-TOSS, an IBM-7090 code written by D. Bagwell for computing transient and steady state temperatures, was used for this purpose (9). The calculations were carried out in cooperation with G.H. Llewellyn and E.I. Wroblewski.

SIFT generates the necessary input for TOSS. The input for SIFT consisted essentially of: (1) a two-dimensional geometrical configuration in cylindrical coordinates, (2) specification of the materials involved and their thermal properties at the operating temperatures, including heat generation rates (a function of neutron flux), (3) boundary conditions for different modes of heat transfer, conduction, convection and radiation, and (4) an initial guess of the temperature in each portion of material, based on prior results of similar programs for Dresden reactor pins. The input for TOSS generated with SIFT was a mesh point or nodal arrangement of the capsule, each node exhibiting the properties of the surrounding mass. The iterations were based on a trial-and-error heat balance. Finally, the output gives a very detailed temperature distribution in the capsule. From these results we can determine the error caused by the introduction of the thermocouple and establish the correspondence between the temperature measured and that of the hottest point in the fuel. The results also give the temperature difference between the two ends of the seal. Unfortunately because of the restricted time, the program did not reach a steady state solution and, more important, because of the recent changes in design, the results obtained are not representative of the actual capsule. It was decided that when the design is finished, a SIFT-TOSS calculation should be made to get the appropriate information. Results from a calculation made by A.F. Zulliger with another program, MAMU, which considers only heat transfer in the radial direction, were kindly made available to us. This constitutes the source for the information on temperatures at different locations that are given in the Results.

4. EXPERIMENTAL PROCEDURE

4.1 Calibration of the Thermocouples

The range of interest was from 1500 to 2500°C. Three W/W25Re thermocouples were used: one bare wire thermocouple served as a reference; the other two were beryllia-insulated and thoria-insulated thermocouples with a tungsten protective sheath.

For the calibration work an electrical furnace was used (see Fig. 3). This furnace had been used before in similar experiments by W.W. Johnston and M.H. Cooper, from the Instrumentation and Controls Division, and the experiments were run with their help and supervision. The highest temperature reached in previous experiments was close to 2200°C.

The "true" temperature was read with a pyrometer calibrated against a standard tungsten lamp. Measurements of the thermoelectric emf generated by the thermocouples were made with a potentiometer. A multipoint recorder (millivoltmeter) was also kept on line to give a record of the variation with time of the emf's of the thermocouples.

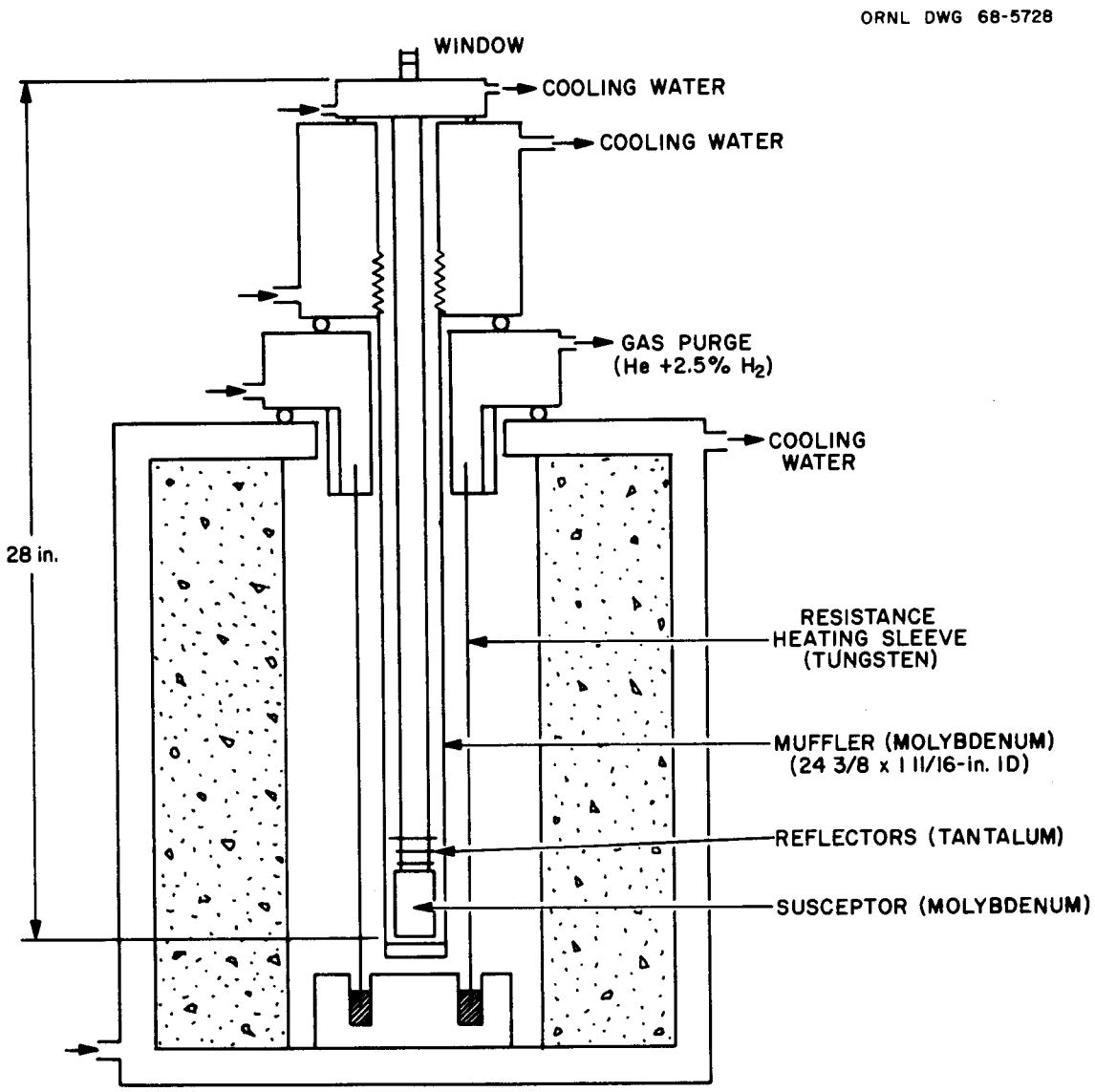

Fig. 3. Furnace

The furnace consisted of a thermally insulated, tungsten sleeve heating element with a surrounding water-cooled jacket. The muffler, a thick-walled molybdenum tube closed at the bottom was located inside the tungsten sleeve with an argon atmosphere between them. The thermocouples were placed in the susceptor, a molybdenum cylinder with a black body hole in it. The bare wire thermocouple was kept in place mechanically with Mo springs, and part of the cylinder served as a hot junction (Fig. 4). Tantalum reflectors above and below the susceptor helped in centering the thermocouple in the muffler and reduced free convection; thus minimizing temperature gradients and improving the black body behavior of the susceptor. The quartz sighting window and the prism at the top had been calibrated together with the pyrometer. Once the thermocouples were located in the susceptor and the susceptor was hung from the top cover of the furnace, vacuum degassing was carried down to 50 μ of Hg. The operation continued with the initial heating of the furnace; then a mixture of He and 2.5% H_2 was introduced to prevent oxidation. Successive vacuum and helium filling was necessary to reduce the amount of O_2 to a minimum. The pressure of the gas mixture was kept slightly above one atmosphere to prevent any air leaks into the system. The thermocouple, stranded wire, emerging from the furnace through a teflon and epoxy-resin seal, was directly connected to copper wire by a mercury drop. The drops were kept in an ice bath at 0°C to provide the reference cold junction. No extension leads were used. The equivalent electrical circuits and the probable shunting effects between wires and between wires and sheath are indicated in Fig. 4. The constancy of the resistancy of each thermocouple has been used to check that no parasitic point of contact had appeared during the installation of the susceptor in the muffler.

4.2 Problem of the Seal

The seal was needed to keep fission gases from escaping at the point where the thermocouple wires came out of the capsule (Fig. 2). The seal consists of an alumina cylinder with two nickel tubes to put the wires through (Fig. 5). The sealing is to be made with silver solder. Generally, this type of seal is used with solid wires so the silver solder does not have to fill the tube to make a good seal. The rest of the tube can be filled with an insulator material.

Since stranded wires are to be used in this case, the silver solder fills up the nickel tube giving a continuous contact and increases the temperature difference between the two extremes when the seal is placed across a temperature gradient.

To run an experiment reproducing the exact working conditions was not justifiable because of the involvement in experimental apparatus and the dubious accuracy, due to the small size of the seal. Considering that the operating temperatures vary between 200 and 300°C an equivalent experiment was performed.

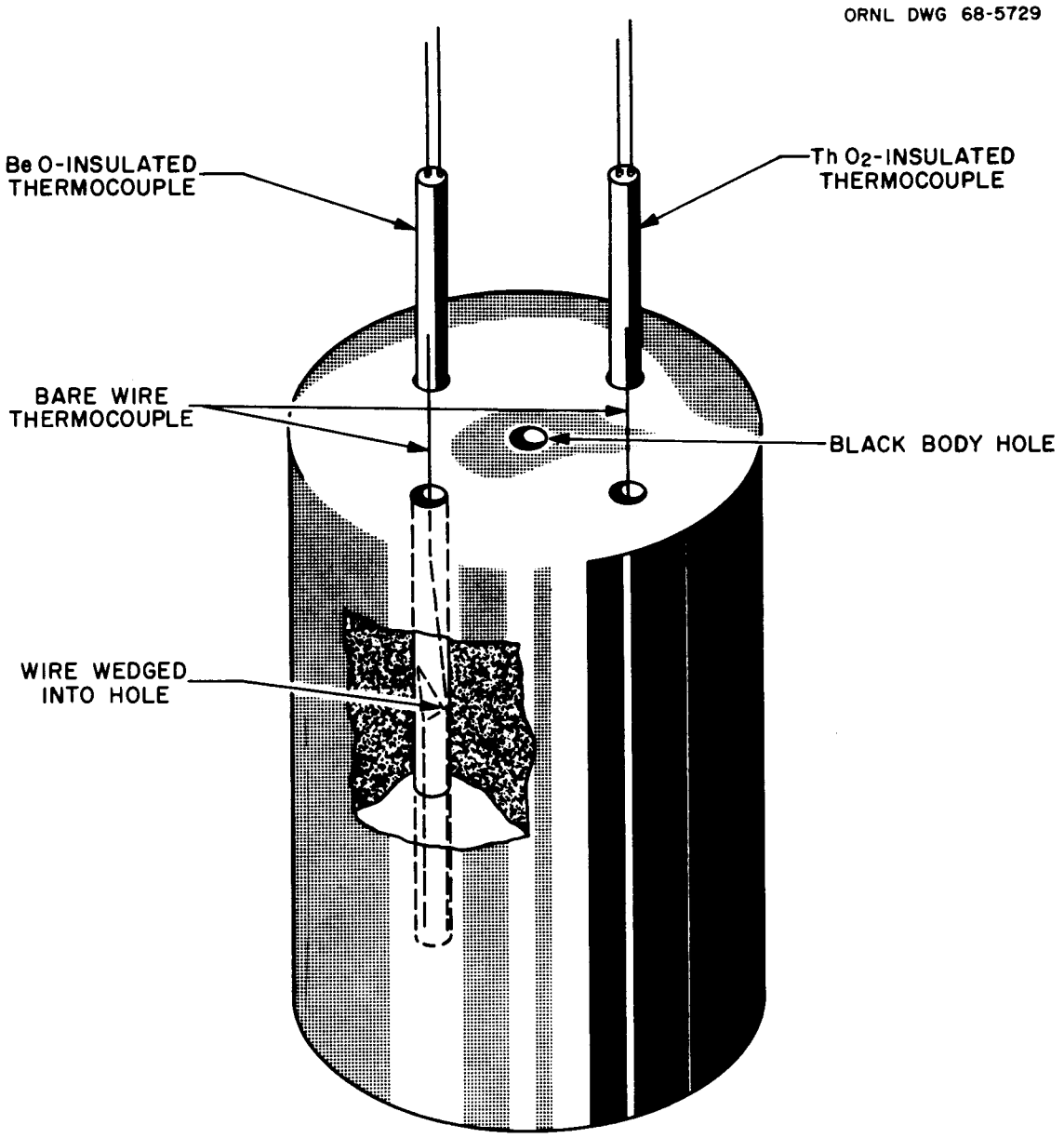

Fig. 4. Schematic of Molybdenum Susceptor

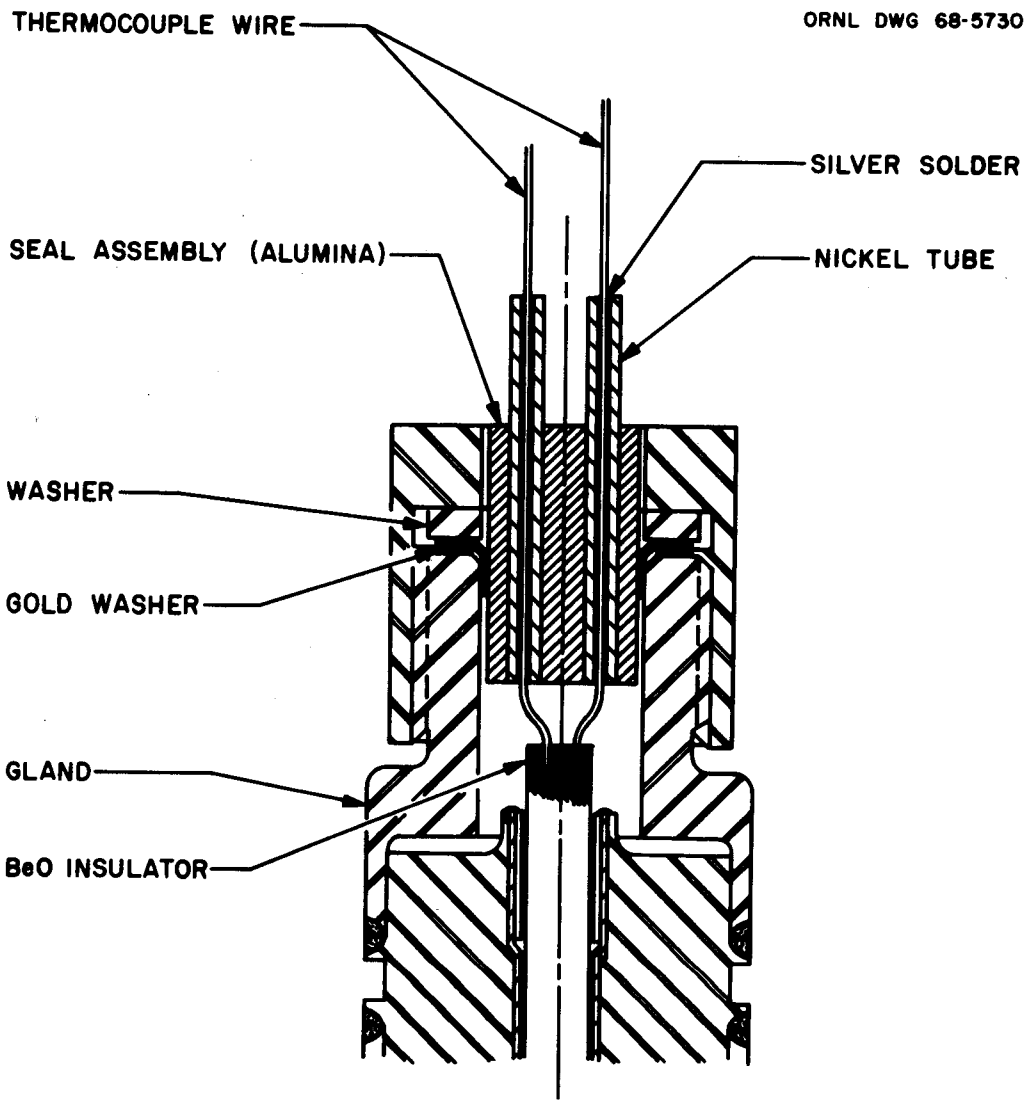

Fig. 5. Cross Section of Top of the Capsule Showing the Seal

Correction was needed for a voltage change in each thermocouple wire due to a current in the circuit formed by the nickel tube, the silver solder and the thermocouple wire in the seal. The current was caused by a thermal emf. If the current were known, the voltage change could be given by Ohm's Law. It can be shown (see Appendix 8.2) that the correction is only a function of the ratio of the resistances of the three different conductors between the two ends of the seal, and of the temperatures at the same points; a continuous contact is not necessary.

Two experiments were run with three wires: thermocouple, silver, and nickel, adjusting the ratio of their lengths to match the respective resistances in the seal. Both thermocouple wires were tested. The cold junction was kept in ice at 0°C and the hot junction was kept in a mineral oil bath in which the temperature varied between 25° and 200°C. In this experiment the resistance of the silver for the current going from the thermocouple wire to the nickel tube was neglected, since it is much smaller than the resistance along the tube axis ($D/L << 1/10$).

4.3 Extension Leads

A similar setup was used to determine the correction needed due to the extension leads. The hot junction is at 120°F in the cooling water zone of the reactor and the cold junction at room temperature or in ice outside the reactor.

5. RESULTS AND DISCUSSION

5.1 Temperature Profile

Because recent changes have been made in the design of the capsule, it was decided to wait until the design of the capsules is completed before running a final SIFT-TOSS calculation on the computer. Otherwise the results would be of no use. A calculation made by A.F. Zulliger with a MAMU program (taking radial heat transfer as the only way of dissipation of energy) was made available to us. For a centerline temperature of 2315°C the hot junction of the thermocouple will be at 1870°C. This first estimate gives an idea of the magnitude of the error in the measurement caused by variation in the temperature distribution. The accuracy of this estimate depends on the property data used for the different materials in the capsule. It is also restricted in the mechanism of heat transfer. Nevertheless, the difference in temperatures is definitely the largest of all the errors expected in the system. The lower temperature surrounding the thermocouple probe favors the performance of the electrical insulator. Also from the results of MAMU, the average temperature in the seal of the capsule should be about 290°C. There is no information on what the temperature gradient across the seal would be, but it is expected to be very small.

According to preliminary results obtained with TOSS for a ℄ temperature of 2010°C, the tip of the thermocouple will be at 1834°C, that is, a difference of 176C°. Although this result corresponds to a stage in which the steady state was not yet reached in the computation, it shows the importance of considering axial heat transfer in the calculation. The difference of 445C° calculated with MAMU appears to be too large. As for the seal, for a ℄ temperature of 2010°C, the average temperature in the seal was calculated to be 138°C with a difference of less than 2C° between the ends of the seal.

5.2 Calibration Work

Shown in Figs. 6 and 7 is the variation of the temperature measured by the three thermocouples versus time. Beryllia seems to be the best insulator for the present case, according to the small deviations shown by the beryllia insulated thermocouple. Also, beryllia exhibits better behavior than thoria under irradiation which makes it even more attractive. Thoria shows rather large deviations.

Up to 1600°C no deviation occurred, the pyrometer and the three thermocouples being in agreement within 10C°. After 1850°C the thoria insulated thermocouple showed some fluctuations, presumably due to electric shunting effects. Until the maximum temperature of 2327°C was reached, the BeO thermocouple showed very good agreement with the pyrometer and the bare wire thermocouple.

The measured temperatures are shown in Table 1, and the results plotted on the reference standard curve for bare wire W/W25Re are shown in Fig. 8. Beryllia gave a maximum deviation of 1% with respect to the pyrometer, which is the accuracy obtainable from bare wire W/W25Re thermocouples. Therefore, the standard calibration curve can be used for the beryllia insulated thermocouple.

It was planned to make measurements on the way down in temperature, but after the first one at 2050°C, the heating element broke so that it was impossible to stabilize the temperature. The fact that thoria showed the highest temperatures at certain points may come from shunting at the level at which the rupture was occurring. The reduced thickness of the heating element at this spot caused a higher heat generation increasing the temperature.

It is interesting to note here the performance of the hot junction of the thermocouples. The first run was made using an electron beam welded junction for the two insulated thermocouples. After an agreement within 1.5C° until 1200°C between all the thermocouples and the two pyrometers, the power supply was cut several times by the safety controls and could not be turned back on quickly. This gave some oscillations between 1000°C and 1200°C during which the hot junction broke. This is very common, because of the recrystallization in the wire caused by the heating when the welding is done.

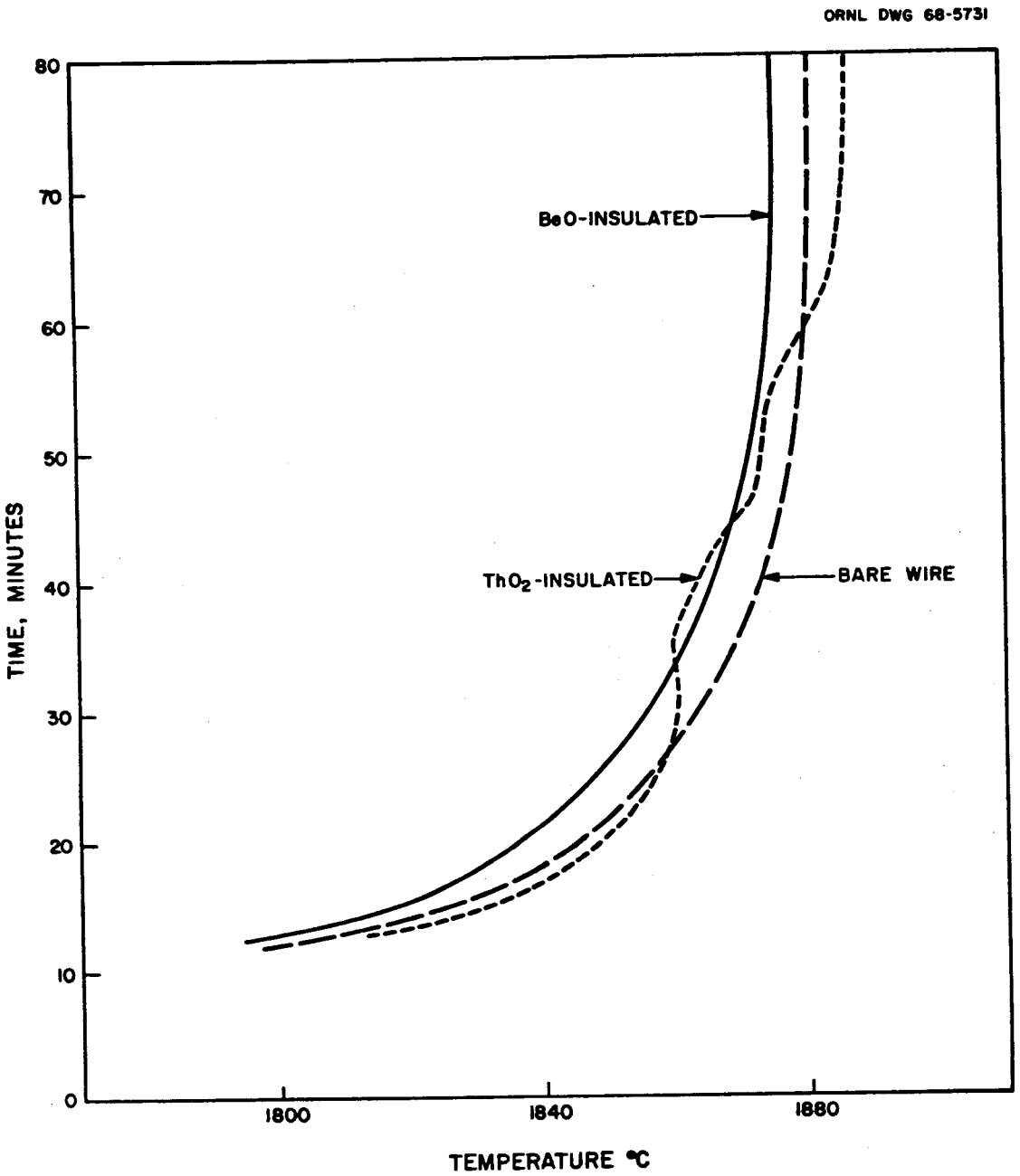

Fig. 6. Thermocouple Temperature vs Time

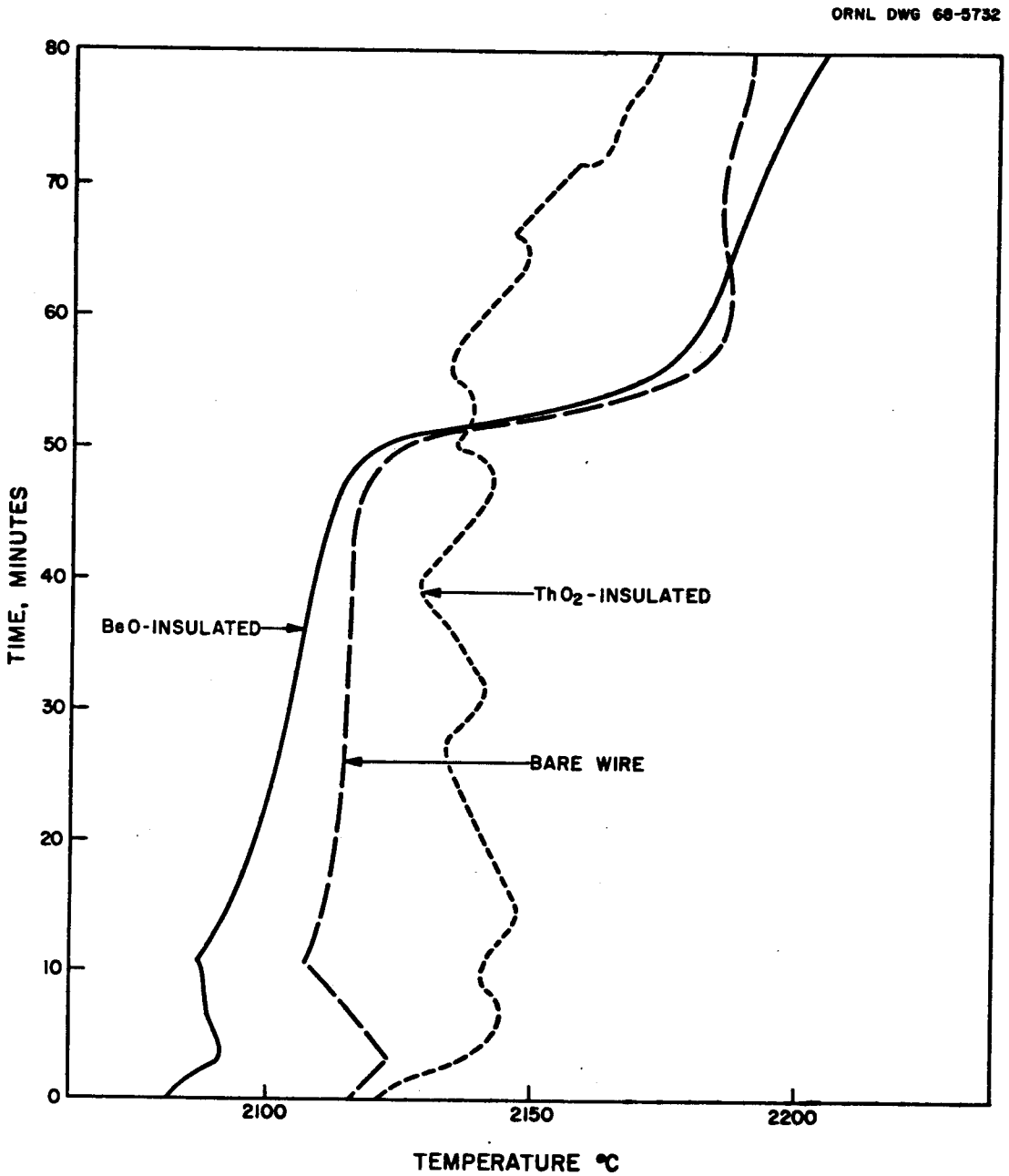

Fig. 7. Thermocouple Temperature vs Time

Table 1. Results of the Calibration Work

Temperature Read by Pyrometer (°C)	Beryllia-Insulated Thermocouple		Thoria-Insulated Thermocouple		Bare-Wire Thermocouple	
	Temperature (°C)	Difference from Pyrometer Reading (C°)	Temperature (°C)	Difference from Pyrometer Reading (C°)	Temperature (°C)	Difference from Pyrometer Reading (C°)
1590.4	1595	+ 4.6	1595	+ 4.6	1600	+ 9
1869	1868	- 1	1874	+ 5	1882	+ 13
1875	1870	- 5	1890	+ 15	1882	+ 7
2102	2080	- 22	2150	+ 48	2115	+ 13
2115	2100	- 15	2150	+ 35	2115	+ 0
2132	2114	- 18	2152	+ 20	2128	- 4
2235	2232	- 3	2170	- 95	2232*	- 33
2295	2295	0	2230	- 65	2265	- 30
2327	2320	- 7	2285	- 42	2260	- 67
2053	2056	- 3	2060	+ 7	-	-

*At this point one of the suspensor wires bent because of the dilatation at high temperature and made contact with one of the thermocouple bare wires.

Before 1500°C all the readings were in agreement by less than 1.5C°.

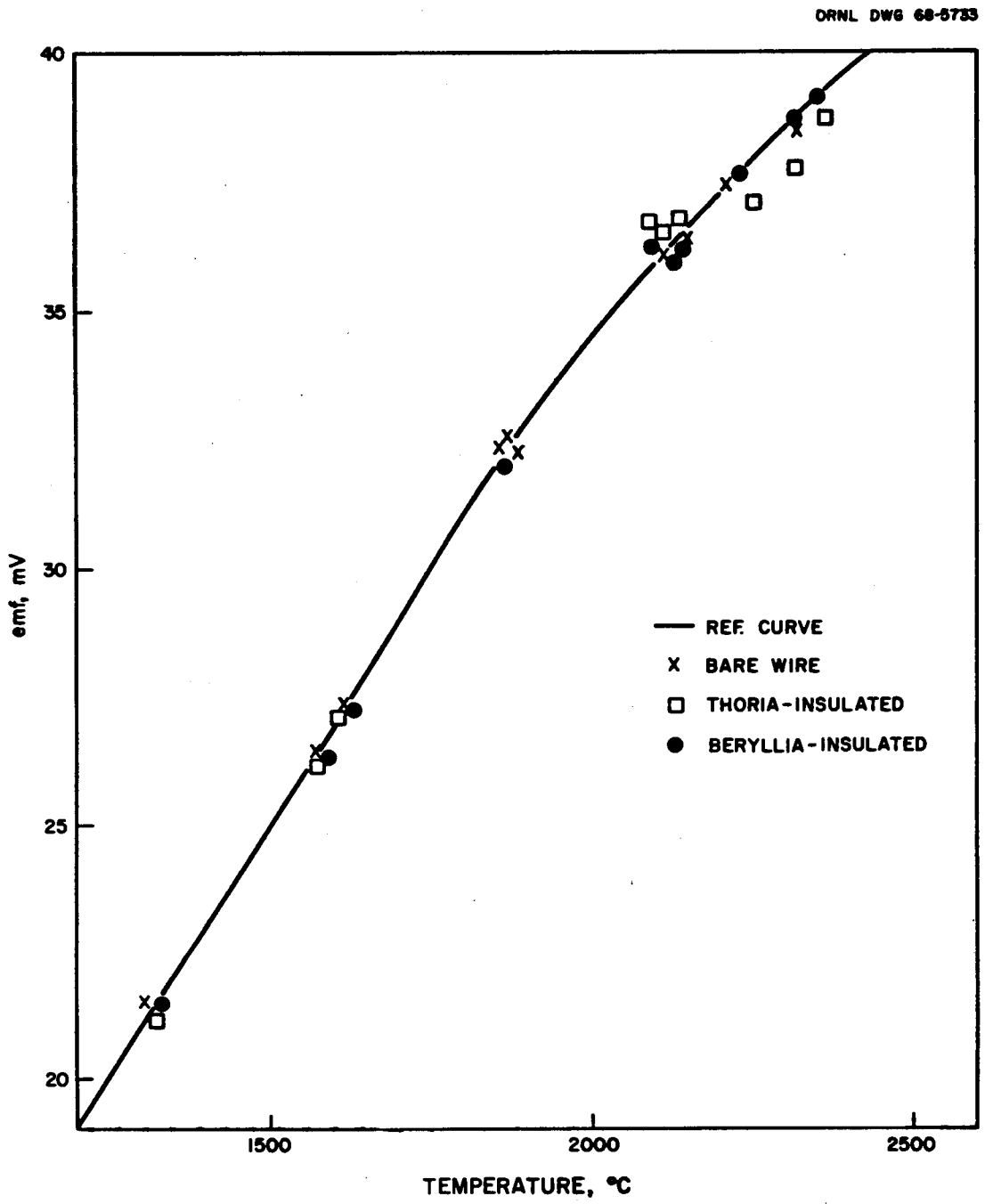

Fig. 8. Emf vs Temperature: Experimental Points Plotted on Standard Calibration Curve for Bare Wire W/W25Re

For the second run a mechanical junction made by a double knot was used. This was supposed to give a good electrical contact because the products given by any oxidation are volatile in this case.

Some vaporization occurred during the experiment. The susceptor was much more shiny than before. The tantalum reflector was brittle, and a white deposit was formed in the susceptor wires at the beginning of the cooled zone. Samples should be taken for analyses.

5.3 Lead Wires

MTR regulations require the use of lead wires of copper alloys, like the ones commonly employed with Pt/Pt-Rh thermocouples. Experimental measurement of the thermal emf generated between the lead wires and the thermocouple wires is shown in Fig. 9. The hot junction will be made in the cooling water zone of the MTR at 120°F (49°C). The cold junction, outside the reactor, will be at 0°C. For these two temperatures 0.166 mv should be subtracted from the reading of the thermocouple. If these two temperatures are kept constant throughout the operation, this correction is the same regardless of the temperature of the fuel.

5.4 The Seal

Experimental measurement of thermoelectric effects generated in the seal was made for both thermocouple wires. Figure 10 shows how the wires were arranged for the measurement. The emf's are of opposite sign so they add together to give the net correction shown in Fig. 10 for the thermocouple reading as a function of temperature drop across the seal. Values were taken up to 200°C; for higher temperatures the curves were extrapolated.

Recent changes in design provided a larger Zircaloy-2 cap atop the last fuel pellet in the capsule; this modification increased the amount of heat transferred in the radial direction in the cap introducing a smaller temperature drop between the ends of the seal. Once the temperatures are known by the calculations with SIFT-TOSS, the corresponding correction can be readily calculated. At 290°C average temperature, a ΔT of 10C° will give an emf of 100 μv. This is equivalent to a +7C° correction in the instrumental reading of the thermocouple.

It has been checked during the experiment that the number of points of contact between the wires is irrelevant to the emf generated. This was possible by twisting the wires together but always keeping the same ratio of resistances as in the seal.

By dividing all the lengths by two, we could see that the correction was a function of the ratio of resistances but not of their absolute magnitude, as it was found theoretically by applying Kirchhoff's Law.

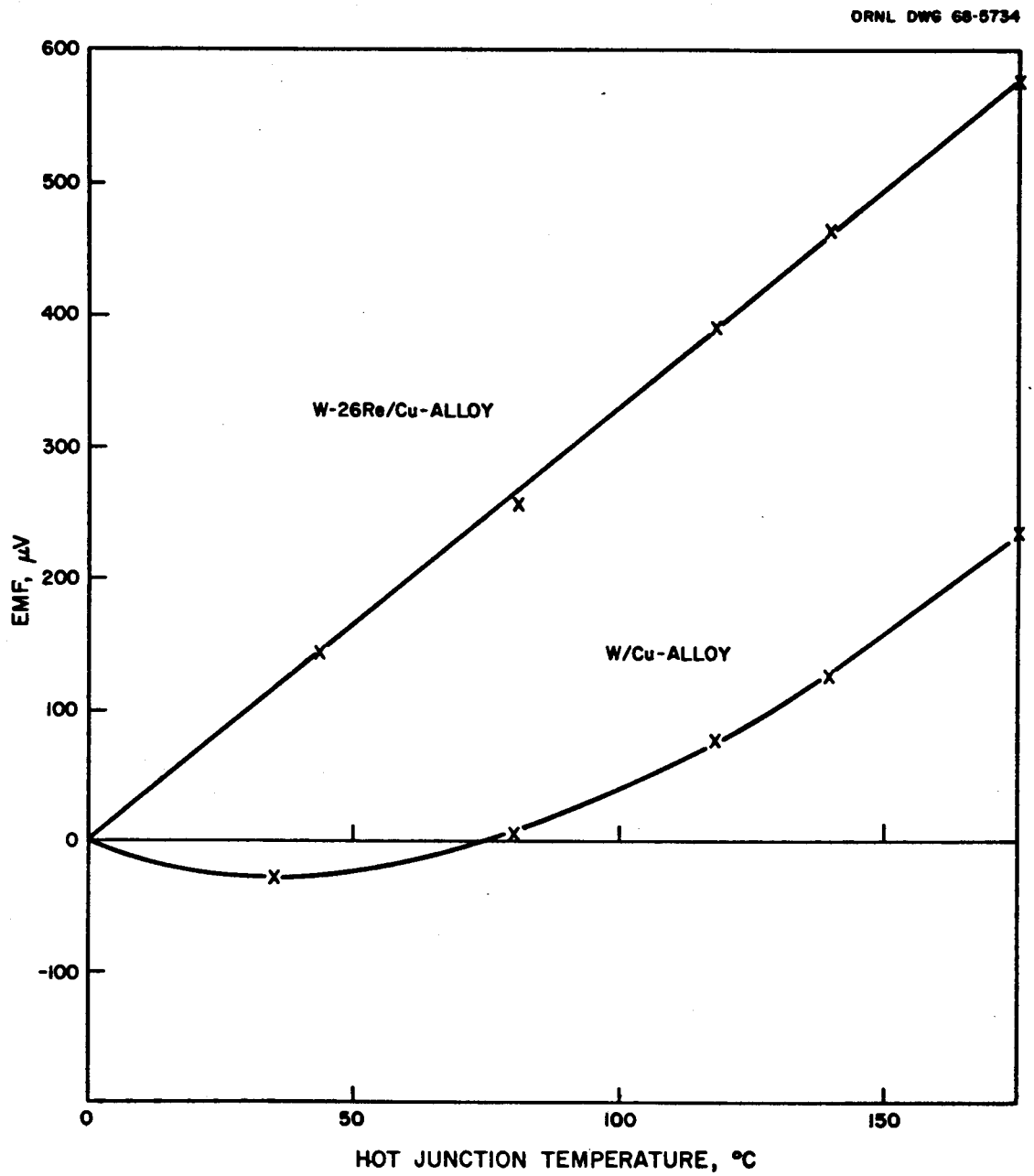

Fig. 9. Parasitic Emf on Thermocouple Wire Relative to Lead Wire

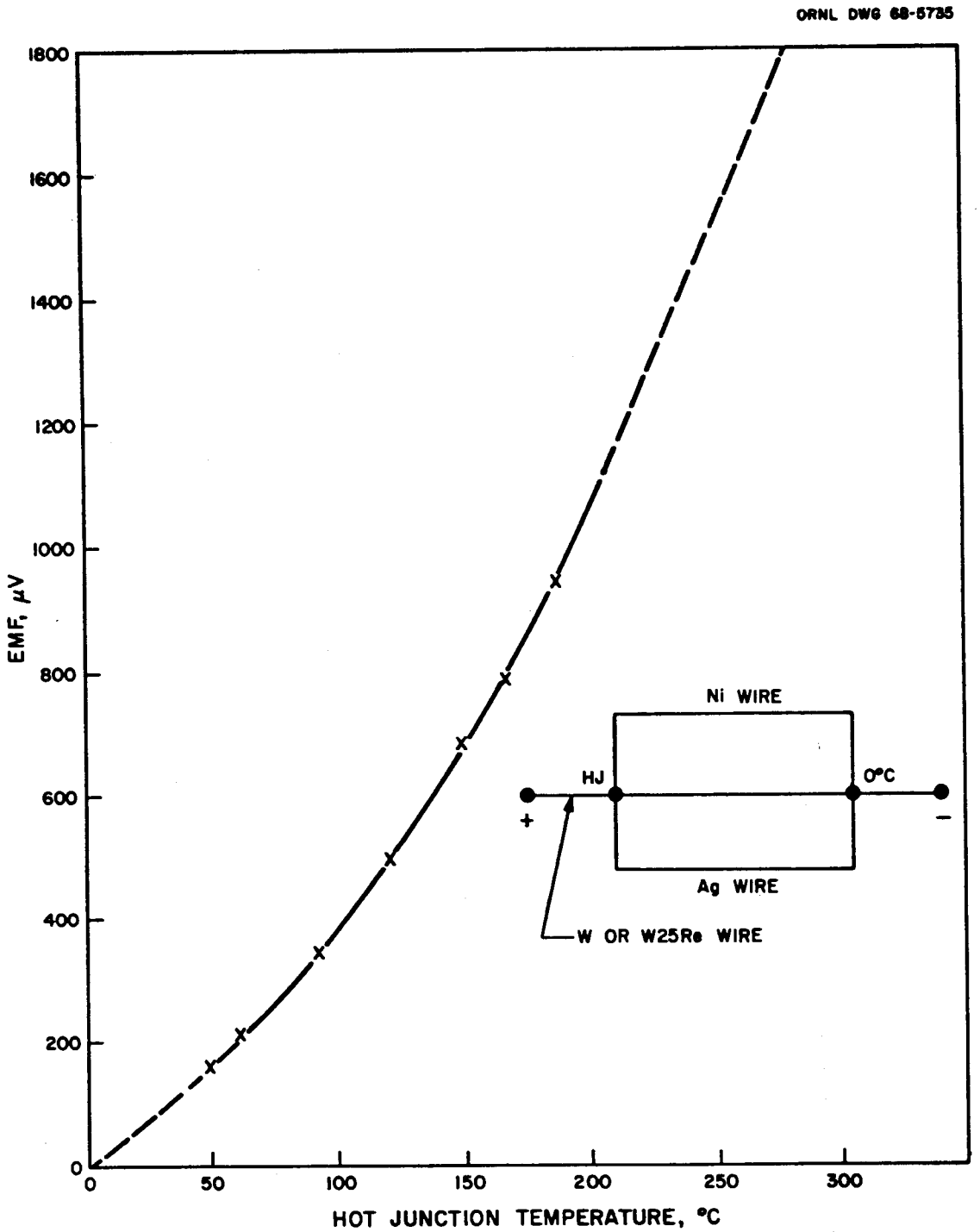

Fig. 10. Results for the Seal

5.5 Transmutation Effects

W.E. Browning and C.E. Miller (2) have studied the effects of irradiation in different thermocouple materials. They report detailed information on this effect, and depending on the length of the experiments, correction can be made for this effect. Their study indicates changes for W wire from 100% to 98% in one year, the product being Re. In a W25Re after one year, Re goes down to 22% and transmutes into Osmium. Accordingly a 10% variation on the emf output will occur after one year, and approximately 1% after five weeks.

5.6 Alternatives

If the same experiments had to be carried out at higher temperature, hafnia should be considered as a possible insulator (10). It also seems possible to use a coaxial design for the thermocouple similar to that of Novak and Asamoto (4). In this design, the tungsten sheath of the thermocouple would be used as one leg and a tungsten Re alloy wire for the other leg. The single wire would be kept in tension by a spring placed in a colder zone. A small gap of He should be kept between the Zircaloy casing and the UO_2 to avoid the possibility of an electrical junction between the tungsten sheath and the Zircaloy casing through the UO_2, giving the same problem as in the seal but with a bigger difference of temperature. For the same reason the wall thickness of the tungsten tube needs to be increased in the section crossing the Zircaloy cap. During the calibration experiment tungsten-rhenium-25 cable was found to be a good spring even at high temperature and could be used in this case. The seal through the alumina has already been used in an experiment of this type (4). At the top of the sheath a piece of BeO insulator is used to center the W-Re wire. The different weldings can be made by electron beam welding.

6. CONCLUSIONS AND RECOMMENDATIONS

The greatest error is produced by variation in the temperature profile due to the presence of the probe.

It was found that beryllia insulation gave most satisfactory results and therefore should be used in the final design.

The hot junction should be made with a double knot instead of by welding the wires by electron beam. The welded junctions are extremely fragile and may break during the measurements. The double knot junction made good electrical contact.

The calibration curve for the bare wire thermocouple should be used for the beryllia insulated thermocouple also, since the agreement they gave was within the accuracy indicated by the manufacturers (1%).

Corrections for the seal are readily obtainable as a function of temperatures at the extremes.

As for the extension leads, if the temperatures are not varied (120°F and 0°C), the correction for the reading will be -0.166 mv.

It will be necessary to continue the work on the SIFT-TOSS program to analyze the results from the experiments at MTR.

Exact corrections for transmutation of the W/W25Re wires can be calculated from data in the literature.

If more detailed information is desired about shunting effects with thoria, a test with a broken hot junction thermocouple should be run. The curve of resistivity versus temperature would probably be in steps.

7. ACKNOWLEDGEMENTS

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8. APPENDIX

8.1 Thermoelectricity

Seebeck Effect. An electric current flows continuously in a closed circuit of two dissimilar metals when their junctions are maintained at different temperatures.

Thermoelectric laws:

1) The law of the homogeneous circuit. An electric current cannot be sustained in a circuit of a single homogeneous metal, however varying in section, by the application of heat alone.

2) The law of intermediate metals. If in any circuit of solid conductors the temperature is uniform from point P through all the conducting matter to point Q, the algebraic sum of the thermoelectromotive forces in the entire circuit is totally independent of this intermediate matter and is the same as if P and Q were put in contact. From this law the expression below follows:

$$E_{AB} = E_{AC} + E_{CB}$$

Thus, the emf for a thermocouple AB between temperatures T_1 and T_2, is the algebraic sum of the emf's of two thermocouples AC and CB, both between T_1 and T_2.

3) The law of intermediate temperatures. The thermal emf developed by any thermocouple of homogeneous metals with its junctions at any two temperatures T_1 and T_3 is the algebraic sum of the emf of the thermocouple with one junction at T_1 and the other at any other temperature T_2 and the emf of the same couple with the junctions at T_2 and T_3. Thus,

$$E_{T_1T_3} = E_{T_1T_2} + E_{T_2T_3}$$

8.2 Demonstration of the Validity of the Test for the Seal

To clarify this point and see the influence of the different factors we shall solve the problem mathematically. Suppose that in the actual seal there is a finite number of contact points between the nickel, the silver, and the thermocouple wire. The electrical circuit between two successive contacts M and N is represented by the equivalent scheme (Fig. 11) with two different emfs due to the temperature difference between the junctions.

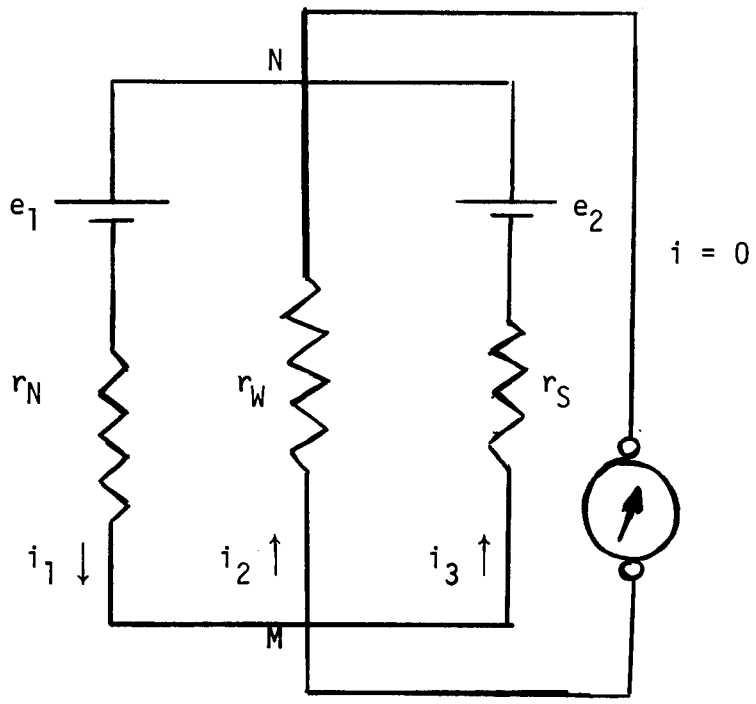

Fig. 11. Schematic Diagram of Equivalent Circuit Between Contacts M and N Between Three Wires

By application of Ohm's and Kirchhoff's Laws to the circuit, we get the emf along the portion of the thermocouple wire which will change the reading of the total emf of the thermocouple. We have:

$$e_1 = r_N i_1 + r_W i_2 \qquad \text{(1) for the Ni-W (or W-Re) loop}$$

$$e_2 = - r_W i_2 + r_S i_3 \qquad \text{(2) for the Ag-W (or W-Re) loop}$$

$$i_1 = i_2 + i_3$$

e_1 is equal to the algebraic difference between the thermal emf's Ni-W at the temperatures of the points M and N. e_2 is related to W-Ag. By adding (1) and (2) we get the equation for the Ni-Ag loop with an emf $e_1 + e_2$ which is also equal to e_3 related to Ni-Ag.

If dE is the voltage change in the W wire,

$$dE = r_W i_2$$

Eliminating i_1 and i_3 from the qualities above,

$$dE = \frac{e_3 \cdot r_S + e_2(r_S + r_N)}{r_S r_W + r_W(r_S + r_N)} (r_W)$$

Now if we assume that r_S, r_N, and r_W are in the same ratio as resistances R_S, R_N, and R_W, we can write the same equation with R's.

By summation over all the points of contact, we have for the total emf

$$E = \Sigma dE = \frac{\Sigma e_3 R_S + \Sigma e_2(R_S + R_W)}{R_S R_N + R_W(R_S + R_N)}(R_W)$$

From thermoelectric laws, $\Sigma e_3 = E_{NiAg}$ and $\Sigma e_2 = E_{AgW}$ (see Figs. 12a and 12b) between the temperatures T_1 and T_2 independently of the temperature profile so that

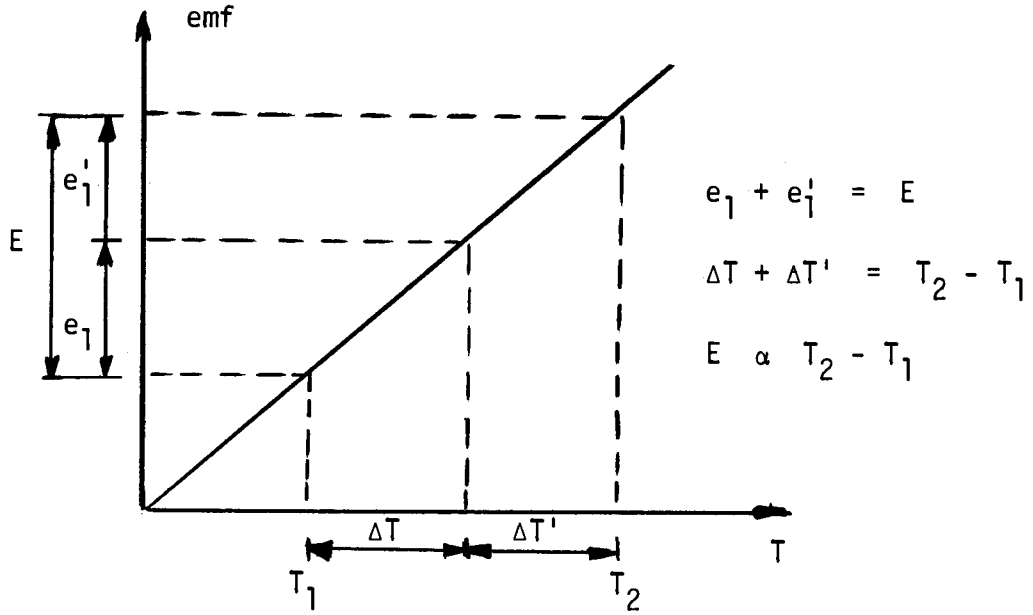

Fig. 12a

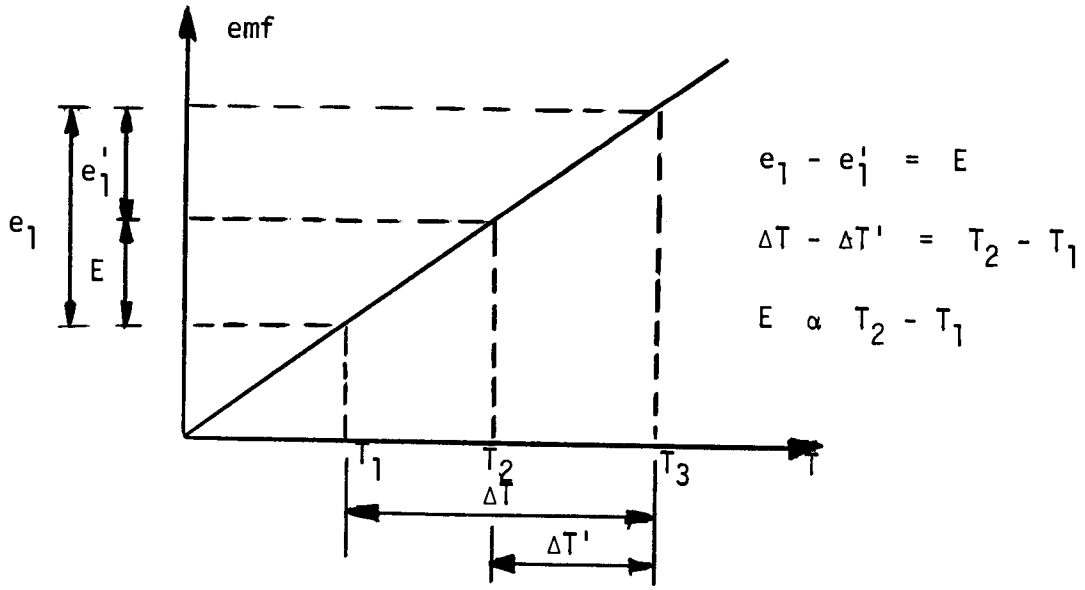

Fig. 12b

Fig. 12. Emf vs Temperature for (a) Ni-Ag and (b) Ag-W Thermocouples

$$E = \frac{E_{NiAg} \cdot R_S + E_{AgW}(R_S + R_N)}{R_S R_N + R_W(R_S + R_N)}$$

which is the same expression for the circuit of the experiment with the three wires.

E_{NiAg} values are found in the literature. E_{AgW} had to be measured experimentally because of the different compounds added to the thermocouple wire to avoid brittleness. An experiment was made to get E_{AgW} and E_{AgWRe} for two thermocouple wires. The calculation above was made for the two wires with a ΔT of 100C°, giving an agreement of 10% with the experimental data.

If the choice of the metal were not limited by their compatibility, it should be better to use a compound such that the two emf's are of opposite sign. This could be done by adding some compound to the silver.

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