LA-DC-7055 (Presentation Version)

CONF-651002-7

85313

OCT 27 1965

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

MASTER

ANALYTICAL MODEL FOR STUDY OF THERMOCOUPLE ERROR
ATTRIBUTED TO ELECTRICAL CONDUCTION IN INSULATION

By

C. R. Tallman, Industrial Staff Member*

University of California
Los Alamos Scientific Laboratory
Los Alamos, New Mexico

To be presented at the Twentieth Annual Conference and Exhibit
presented by the Instrument Society of America, October 4-7, 1965.

*Work performed at Los Alamos under the auspices of the U. S.
Atomic Energy Commission, Contract W-7405-ENG-36 while the author
was on temporary assignment at Los Alamos from Aerojet-General,
Sacramento, California.

RELEASED FOR ANNOUNCEMENT
IN NUCLEAR SCIENCE ABSTRACTS

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

ANALYTICAL MODEL FOR STUDY OF THERMOCOUPLE ERROR
ATTRIBUTED TO ELECTRICAL CONDUCTION IN INSULATION

By

C. R. Tallman, Industrial Staff Member

University of California
Los Alamos Scientific Laboratory
Los Alamos, New Mexico

Thermocouples are used deep within the core of the Kiwi and Nerva nuclear reactors for both power control and diagnostic measurement. Thermocouples still appear to be the most practical means of determining simultaneously the graphite uranium fuel temperature at many locations in the core during a reactor run.

In designing thermocouples for this application, one of the most challenging problems is the choice of materials compatible with the environment of hot hydrogen, hot graphite, and intense nuclear radiation. A perfect solution to this problem has not yet been found for temperatures approaching 4500°F. Another significant consideration in designing a thermocouple for this temperature range is the effect of the degradation of the electrical insulation. Of all insulator materials presently known, BeO appears to exhibit the highest resistivity vs. temperature property, although the resistivity of BeO decreases rapidly in an exponential manner with temperature, as shown in Figure 1.

The most satisfactory thermocouple to date for the Kiwi and Nerva environment is a refractory metal sheathed, BeO insulated thermocouple using thermo-elements of W/W-26 Re. This paper will concentrate on the errors observed in thermocouples of the above materials of 1/8" OD or less, which can be attributed to the progressive failure of the insulator with increasing temperature.

At high temperatures the electrical conductance of the insulator increases with respect to the thermocouple lead wires, causing a significant shunting of the thermocouple signal. This error is dependent upon the length of the material exposed to the high temperature and the temperature distribution

along the thermocouple length. The error can be either positive or negative, as will be illustrated in the results presented later.

Errors of several hundred degrees F have been observed in thermocouples used in reactor tests. This deviation from the predicted core temperature is of major concern to the reactor designers and to instrumentation personnel, because it necessitates re-examination of both the thermocouple design and the analytical model used to calculate the core temperature.

A digital calculation was made to evaluate the effects of wire size, insulator size, and temperature profile on the error due to insulator conduction, in hopes of minimizing the shunting error. Because of uncertainties in the BeO resistivity, wire-to-insulator contact, and insulator-to-sheath contact, it was realized that a precise quantitative calculation of the error was impossible although the effect of variation of these parameters could be ascertained.

Analytical Model

The distributed parameters such as wire resistance, insulator resistance, and thermal emfs were converted into lumped parameters for each inch of the thermocouple length. This lumped model formed an electrical network of batteries and resistors. The resultant currents were determined by using a digital computer to solve the loop equations by a matrix method.

The emf output of any thermocouple is a result of two basic effects: the Thompson emf arises in any conductor due to a temperature gradient, and the Peltier emf occurs at a junction between two materials due to differences in the Fermi levels. The sum of these emfs is called the Seebeck emf and is written as follows:¹

$$(1) \quad S_{AB}(T) = \pi_{AB}(T) + \int_{\text{ref } T}^T (\sigma_A - \sigma_B) dT$$

The Peltier emf between two materials,¹ A and B, follows:

$$(2) \quad \pi_{AB}(T) = T \left. \frac{dS_{AB}}{dT} \right|_T$$

The Thompson emf, resulting from the temperature gradient along each thermocouple, T_{ref} to T , in the thermo-elements A and B is:¹

$$(3) \quad E_T = \int_{T_{\text{ref}}}^T (\sigma_A - \sigma_B) dt$$

where σ_A and σ_B are the Thompson coefficients of wires A and B and can be determined individually by direct measurement. The quantity $(\sigma_A - \sigma_B)$ can be derived from the above equations and the result follows:¹

$$(4) \quad \left(\sigma_A - \sigma_B \right) \bigg|_T = -T \frac{d^2 S_{AB}}{dT^2} \bigg|_T$$

The integral in equation (3) gives the total emf contribution from the total temperature gradient.

The Seebeck emf is given for W/W-26 Re thermo-elements by the Hoskins Manufacturing Company.² This table, adopted November 23, 1962, was used for S_{AB} from 0°F to 4100°F. For temperatures in the range of 3992°F to 5600°F, a tentative table released in October 1964 was used. To obtain the values of the distributed thermal emf, the Hoskins data were fitted by a least squares code to a polynomial in T . Since the tentative table above 4100°F was not statistically of the same value as the range from 0° to 4100°F, the lower range data were given a weight four and the 1964 data were given a weight one in the least squares fitting.

The following fourth degree expression describes the data:

$$(5) \quad S_{AB}(T) = \sum_{n=0}^4 A_n T^n \quad \text{where}$$

n	A_n
0	-2.90129×10^{-2}
1	1.67553×10^{-3}
2	1.96982×10^{-5}
3	-7.96850×10^{-9}
4	9.91660×10^{-13}

For this fit the standard deviation is 0.12 mv in the 1962 temperature range and the largest single error is 10° at 2290°F. In the 1964 data temperature range, the largest error was 55°F at the highest temperature point. These errors are well within the accuracy of the Hoskins data.

Figure 2 shows the fit to the data. The Seebeck emf, the Peltier emf, and the Thompson differential coefficient calculated from the above equations are given in Figure 3.

It was decided that the electrical network model should include both the Thompson emf and the Peltier emf in their appropriate locations, rather than the Seebeck emf alone as has been done in other calculations.³ This model was chosen since it represents more closely the actual thermocouple physics.

The resistance per inch of the tungsten and tungsten 26% rhenium wires was computed from a least squares fit to the resistivity vs. temperature data given by the Hoskins Manufacturing Company.² The resulting resistivity equation for the tungsten is: the resistivity equation for W-26 Re is:

$$(6) \quad \rho_W(T) = \sum_{n=0}^3 A_n T^n \qquad (7) \quad \rho_{W/Re}(T) = \sum_{n=0}^3 A_n T^n$$

N	A _n	N	A _n
0	-1.1408659 x 10 ⁻⁶	0	1.9524361 x 10 ⁻⁵
1	1.1654742 x 10 ⁻⁸	1	2.6495161 x 10 ⁻⁸
2	1.880683 x 10 ⁻²	2	-7.809163 x 10 ⁻¹²
3	-1.252774 x 10 ⁻¹⁶	3	1.3383235 x 10 ⁻¹⁵

The value of the resistor used in the network representing a one inch wire length is as follows:

$$(8) \quad R(T_{av}) = \rho(T_{av}) \frac{l}{A}$$

where A is the wire cross-sectional area and l is the length in the appropriate units.

The resistivity of BeO is not as well defined as that of the thermocouple wire material. It appears that considerable variation can be found in the resistivity vs. temperature as a function of the insulator purity. Unfortunately, the purity is generally not given with the resistivity data.

Direct measurement of the resistivity at high temperatures is a difficult task. Contamination of the sample under test and knowledge of electrode contact area are some of the parameters that are difficult to master.

A collection of data of reasonable consistency is shown in the composite curve given in Figure 1. It is clear that there are uncertainties of $\pm$ a factor of three at the higher temperatures.

One of the sources of this data⁴ is a measurement made using a short open segment of actual sheathed thermocouple which contained a hard fired BeO insulator. The resistance measured between the thermocouple wires was then used to calculate the resistivity of the insulator. In order to account for the electrical contact area between the insulator bead and the internal diameter of the sheath and for the wire-to-insulator area, a resistance paper planar model was constructed. In the model the areas were painted with silver conducting paint corresponding to a cross-sectional metallographic photo taken of the thermocouple. This is shown in Figure 4. The data, treated by this technique, appear consistent with available handbook data.⁵

Similar resistance measurements, reported by J. A. McGurty and Kuhlman of the General Electric Company,⁶ were analyzed by the resistance paper analog technique to derive resistivity. These data were also found to be consistent with other data.

A reasonable fit to the resultant resistivity vs. temperature data was made by an exponential equation (as one would anticipate for semi-conductor behavior). The equation for the resistivity of BeO vs. temperature is then:

$$(9) \quad \ln \rho_{\text{BeO}}(T) = \sum_{n=0}^3 A_n T^n \quad \text{where}$$

N A_n

0 46.848596

1 $-1.8076727 \times 10^{-2}$

2 2.9423033×10^{-6}

3 $-2.3069285 \times 10^{-10}$

The analytic expression for the resistance between conductors in a two hole cylindrical insulator encased in a metallic sheath follows:

$$(10) \quad R(T) = \rho_{\text{BeO}}(T) \frac{1}{L\pi} \left(\ln \left\{ \frac{2s}{d} \left[\frac{1 - (s/D)^2}{1 + (s/D)^2} \right] \right\} - \left[\frac{1 + 4(s/D)^2}{16(s/D)^4} \right] \left[1 - 4(s/D)^2 \right] \right)$$

Where: s is the center-to-center wire spacing

d is the diameter of the thermocouple wire

D is the insulator outside diameter

L is the insulator length

This equation applies when the conductors are in full contact with the insulator and the encasing metal sheath is also in full contact with the insulator.

The resistance from one wire to the sheath is as follows:

$$(11) \quad R_{w-s}(T) = \rho_{\text{BeO}}(T) \frac{1}{L\pi} \ln \frac{1 - (s/D)^2}{d/D}$$

Since it was desired to evaluate the effect of the wire size and insulator size, the analytic expressions (10) and (11) were used in the computation for relative comparison of various geometries. The resistance paper analog procedure was used to determine the effect of insulator electrical contact on the insulator resistance in later calculations.

The network was then constructed, via the computer code, for the junction Peltier emf, the series Thompson emf, and the resistances of the wire and insulator at each one inch increment for the length of thermocouple under study.

The value of each battery and resistor was calculated at the temperature of the corresponding location. Figure 5 shows the manner in which these elements are assembled and used in the calculations.

Figure 6 shows the various model networks. Figure 6a is for a thermocouple without a conductive sheath. Figure 6b shows a planar network for the sheathed thermocouple which includes Thompson emfs in the sheath and the Peltier emfs between the thermocouple wires and the sheath. Figure 6c is a simplified model based upon comparing results of the (b) model with the results of the (a) model for various temperature profiles and thermocouple geometry. In all cases the results from the (c) model were identical

to those obtained with the more complex (b) model. In the simpler model, only the additional conduction between wires, due to the wire-to-sheath path, is included for the sheathed thermocouple. The total resistance in the insulator for this model is given by equation (10).

Analytical Results

Figure 7 shows the error (indicated - true) for various thermocouple insulator diameters and wire diameters for the temperature profiles shown. The junction is maintained at 4500°R (4060°F) and the temperature profile for each insertion length has a different slope. It can be seen that the error increases with insertion length because more of the insulator is hot and thereby creates a larger leakage shunting the signal. As the insulator diameter is reduced, the error also increases because reducing the insulator diameter reduces the insulation resistance. As the wire diameter is reduced, the error increases because the source resistance is increased. Therefore the shunting effect is enhanced.

Figure 8 shows the calculated error as a function of the shape of the temperature profile. The error in the previous figure was negative. In this figure, however, where the thermocouple must reach past a higher temperature zone, the error is positive. In this case the distributed Peltier emfs at higher temperatures are overcoming the shunting loss. Again the influence of the thermocouple geometry is shown. Figure 9 illustrates the hot zone effect. The junction is maintained at a temperature of 2500°R , well below that significant for insulator degradation effects. The error is positive and is shown for two different hot zone lengths, 1 and 10 inches, and for maximum temperatures of 3500 to 5000°R . The influence of wire and insulator diameter on this error is also illustrated.

Figure 10 is typical of the reactor temperature profile. With this type of temperature distribution it can be seen that by varying the wire diameter alone, a definite knee in the curve occurs about a wire diameter of $0.015''$. Increasing wire diameter above $0.020''$ has little effect on the error. The error is not as dependent upon the insulator diameter showing only a 50°R spread for insulators of $0.100''$ to $0.075''$ OD for thermocouple wire of $0.020''$. Thermocouples using $0.020''$ diameter thermocouple wire with $0.080''$ insulator

diameter were selected for reactor use based on these results.

These calculations are for thermocouples which have the wire in full contact with the insulator and the insulator in full contact with the sheath. However it is clear that in actual practice contact is imperfect, being of "point" or "line" nature rather than "full area". With hard-fired insulators, the wire is in minimum contact with the insulator holes (usually 0.002" to 0.003" difference in diameter is typical). The insulator is in minimum contact with the sheath (typical 0.005" diameter difference). Resistance paper analog studies have shown that line-contact will cause the wire-to-wire resistance to be increased by a factor of 2 over the full contact values and the wire-to-sheath resistance to be increased by a factor of 4.

In order to evaluate this effect, the resistivity of BeO was varied over a range of 0.05 to 10 times the value given in Figure 1. Figure 11 illustrates the effect of variation of resistivity on the shunt error, for various thermocouple lengths subjected to the typical reactor temperature profile. The curve labeled 1 is that obtained using the reported insulator resistivity and full contact for a typical thermocouple with 0.035" insulator diameter and 0.005" W/W-26 Re thermocouple wires.

Figure 12 shows how effective a cooled thermocouple performs. Here the major portion of the thermocouple is maintained at 2500°R or less and the last 5" are exposed to a temperature gradient up to 5000°R. (This calculation was made with 0.5" calculational increments rather than 1" increments). It is seen in this case that wire diameters as small as 0.010" show less than 50°R error at 5000°R, while 0.005 wire shown 500°R error. It is necessary to choose a diameter such that the longitudinal heat conduction does not decrease the tip temperature significantly.

Cooled thermocouples are currently being used in the Rover reactors to measure gas temperatures. Techniques are being developed to circulate a cooling gas around the lead of a material thermocouple. By this means we hope to eliminate a major portion of the shunting error and perhaps eliminate some of the high temperature material problems as well.

An existing furnace⁸ with 32" working length was modified to accept standard core thermocouples. These were placed inside the axial holes of a hollow cylindrical graphite tube, 32" long and 2" ID, with a variable wall thickness. Electric current heated the tube which in turn radiated inward to the graphite rod. The variation of tube wall thickness with distance and the placement of suitable radiation shields, external to the radiator tube, ultimately produced the desired axial temperature distribution in the graphite rod and thermocouple. An optical pyrometer measured the graphite rod temperature through six optical windows spaced at about 6" intervals along the length of the furnace. The line of sight proceeded through the windows, through 1/4" holes in the radiator, to the graphite rod wall, and finally to the thermocouple tip which was always located opposite one of the ports. The pyrometer had been calibrated against a National Bureau of Standards tungsten strip lamp, and the window corrections were applied. The furnace could be pressurized with H₂ or He up to 1500 psi. Peak power required was of the order of 150 KW.

In a typical run, furnace power was increased in a succession of steps, pausing long enough on each one to achieve temperature equilibrium. Ten to fifteen steps were made in each run, and runs lasted 30 to 45 minutes. The thermocouple output was recorded on a continuous strip chart recorder. At each plateau the junction temperature was measured by the optical pyrometer. The temperature distribution was measured pyrometrically using all six windows. To provide a consistent set of data, all pyrometer readings were made by a single observer.

Altogether some eighty thermocouples have been studied in the furnace. All have exhibited shunt losses. Figures 13 to 15 show some of the results.

In Figure 13 the thermocouple error, i.e. the difference between thermocouple output and optical pyrometer reading at the junction, is plotted against the (pyrometer) junction temperature. The thermocouples in use were the same type as the reactor core thermocouples which had performed poorly in Kiwi-B-4D. They had 0.005" dia. wires, 0.035" BeO sleeves, and Mo sheaths of 0.065" OD. The junctions were located opposite the 18" port. Five typical furnace temperature distributions are shown. There is a considerable

spread in the error data from thermocouple to thermocouple. We believe that this spread is related to variations in BeO resistance caused by variations in contact between the metals and BeO. Despite the data spread, the trend is clearly that of increasing loss with rising temperature. The curves end at 4460°R, the melting temperature of the Mo-Mo₂C eutectic.

Figure 14 contains data for thermocouples with 0.005" dia. wire, inserted to depths of 18" and 24" from one end of the furnace, and 8" from the other end. Again there was considerable spread in the data from the thermocouples of a given group. Only the average trends of the data are shown. As in Figure 13, the error increases rapidly with junction temperature. As noted in Figure 7, the error also increases with insertion length, or "length at high temperature". Finally there is a slight increase in error between Westinghouse (WANL) thermocouples and the Los Alamos version (LASL) caused by difference in BeO diameter and wire center-to-center distance, which is corroborated by the calculated results given earlier.

In the center of Figure 14 is a short line proceeding from an error of -600°R at 4900°R to -800°R at 5100°R. This is the slope to be expected for a thermocouple whose output is saturated. The output no longer rises as the junction temperature is increased and hence the error increases as rapidly as the tip temperature does. Several thermocouples showed this behavior. Some even gave decreased output with higher furnace temperatures. Generally on reducing furnace temperature the output returned to its earlier value unless the junction had been damaged.

Finally in Figure 15, error curves are plotted for thermocouples whose wire diameters vary from 0.005" to 0.020", while the insertion distance is held constant at 24". As expected the large wires give much smaller errors. It appears that a thermocouple with ≈ 0.020 " wires has a chance of operating with errors of $\approx 200^\circ\text{R}$ in the vicinity of 5000°R, especially if it can be cooled to within a short distance of the junction.

The only direct comparison between measured error and calculated error is given in Figure 15. For the calculation, straight-line approximations to the measured furnace temperature distributions were used. Clearly the trends

agree qualitatively. However, generally the calculated errors are somewhat smaller than the measured errors, which from Figure 10 indicate that the real BeO resistances were lower than those assumed in the calculations. Now the calculations used full-contact resistances when there must really have been point or line contacts. Hence the resistivity of BeO must be considerably lower than that shown in Figure 1 by perhaps as much as a factor of five. Calculations are in progress to determine an effective BeO resistance, which would define the product of form-factor and resistivity. There is presently no indication as to what may be causing a low resistivity: low purity BeO, high surface conductivity, or high gas conductivity.

Only fragmentary data have demonstrated the effect of the distributed Peltier junction, i.e. a net positive error rather than a shunt loss. Three of the first thermocouples tried in the furnace were inserted to a depth of 30". Reference to Figure 15 will show that from 18" to 30" the temperature was higher than that at the tip. Thermocouple output agreed well with optical pyrometer up to about 3900°R, at which point the output exceeded the pyrometer. By the next temperature step the Mo sheath had evidently melted in the region of 24". No other thermocouples have since been run with this temperature profile.

Experiments are in progress to test newer designs of larger diameter thermocouples with higher quality materials and closer tolerances.

Summary of Shunt Effect Study

The shunt-effect calculations appear to confirm at least qualitatively the locally measured shunt losses. Calculations of the distributed Peltier effect agree qualitatively with "hot zone" measurements made elsewhere. Testing continues with temperature profiles resembling those found in Rover reactors, and these results are being compared with the results of the calculations.

Studies are in progress to include the effects of temperature gradients within the insulator due to gamma ray heating. The gamma heating can cause the thermocouple wires to be several hundred degrees hotter than the sheath depending upon the heat transfer from wire-to-insulator and insulator-

to-sheath. This temperature gradient then causes the resistance calculations to be much more complex since the resistivity is non-uniform throughout the insulator. The electrical resistance is influenced by the contact area in two ways: since the heat transfer is directly related to this contact as well. New thermocouple designs are currently under study to minimize the influence of the insulator by providing coolant gas internal to the thermocouple.

ACKNOWLEDGMENTS

Several members of groups N-1, N-3, N-4, and N-7, of the Los Alamos Scientific Laboratory have helped, and are continuing to help, in the development of thermocouples for the Rover Reactors. In particular Dr. J. E. Perry, Jr. contributed significantly to the considerations in the choice of the analytical model. Dr. T. Springer, O. Farmer, and J. Caldwell were of much help in developing the computer programming techniques.

The thermocouple testing by W. Prince and associates of N-7 is appreciated.

B. Goodier and E. Brown of N-4 have contributed and are contributing significantly in the design and testing of thermocouples.

We are indebted to Dr. W. Esselman for permission to quote the results obtained from the Westinghouse Astronuclear Laboratory thermocouples in our furnace.

Several discussions with Dr. G. Gilmour of WANL pertaining to analytical models and computer results were of great value in this work also.

REFERENCES

1. Finch, Donald I., "Temperature, Its Measurement and Control in Science and Industry", 3, 1; C. M. Herzfeld editor-in-chief; Reinhold Publishing Company, New York (1962).
2. Technical Data Sheets originated by Hoskins Manufacturing Co., 445 Lawton Ave., Detroit, Michigan, unpublished.
3. R. J. Freeman, "High Temperature Thermometry Seminar, Held October 1959", USAEC report TID-7586 (1960). Also G. A. Gilmour and G. Collier, WANL, Large Pennsylvania, private communication (1964).
4. W. R. Prince, Los Alamos Scientific Laboratory, Los Alamos, New Mexico, unpublished data (1964).
5. R. E. Long and H. Z. Schofield, "Reactor Handbook", 3, Chapter 1.3 AEC Report AECD-3647 (1953).
6. J. A. McGurty and W. C. Kuhlman, General Electric Co., Flight Propulsion Laboratory Dept., Cincinnati, Ohio. Report number TM-62-4-2, unpublished (1962).
7. All thermocouples of 0.065" OD sheath mentioned in this paper were produced by Aero Research Instrument Co., Inc. Division of American Standards, 315 N. Aberdeen St., Chicago, Illinois.
8. W. R. Prince and W. L. Sibbitt, "High Temperature Reactor Core Thermocouple Experiments" LA 3336-MS, Los Alamos Scientific Laboratory, July 1965.
9. J. E. Perry, Jr. et. al., "Thermocouple Development for Project Rover" presented at the High Temperature Thermometry Conference, February 1965, sponsored by the AEC, Washington, D. C.

SEEBECK EMF
26 RE/W (MV)

FIGURE 2
SEEBECK EMF
VERSUS TEMPERATURE

THERMOCOUPLE CROSS-SECTION

RESISTANCE PAPER MODEL

ALL DIMENSIONS ABOVE
RATIOED TO SCALE UP THE
RESISTANCE PAPER MODEL.

$$R_{w-w} = \frac{\rho}{L} (k)$$

(actual)

$$R_{w-w} = \frac{\rho_{\text{paper}}}{L} (k)$$

(model)

$$k = \frac{R_{w-w}(\text{model})}{R_r}$$

FIGURE 4

FIGURE 6 THERMOCOUPLE CALCULATION MODELS

FIGURE 9
THERMOCOUPLE SHUNT ERROR
VERSUS HOT ZONE TEMPERATURE
JUNCTION AT 30", 2500°R
HOT ZONE 1" OR 10" LONG

	WIRE DIA.	BeO DIA.
1	.015"	.075"
2	.020"	.085"
3	.025"	.095"

FIGURE II
THERMOCOUPLE SHUNT ERROR
VERSUS JUNCTION LOCATIONS
BeO RESISTANCE VARIED BY
FACTORS SHOWN FROM FULL
CONTACT VALUE (1.0) ASSUMED
IN FIG. 4d.

FIGURE 12
THERMOCOUPLE SHUNT ERROR
VERSUS JUNCTION TEMPERATURE
SHEATH COOLED TO 25", JUNCTION AT 30"

CURVE	WIRE DIA.	Be O DIA.
A	.025"	.095"
B	.020"	.085"
C	.010"	.075"
D	.005"	.065"

FIGURE 13
THERMOCOUPLE SHUNT ERROR
VERSUS JUNCTION TEMPERATURE
WIRE DIA. = .005"
Be O DIA. = .035"
Mo SHEATH DIA. = .065"
18" INSERTION INTO MKI FURNACE
SIX THERMOCOUPLES TESTED

TC ERROR = TC - OPTICAL PYROMETER, °R

FIGURE 15
THERMOCOUPLE SHUNT ERROR
VERSUS JUNCTION TEMPERATURE
TC INSERTION = 24"

TC CHARACTERISTICS						
	No.	WIRE DIA.	WIRE CL TO CL	BeO DIA.	SHEATH	
					DIA.	MATL.
A	1	.020"	.035"	.082"	.125"	Mo
C	1	.010"	.015"	.040"	.065"	Ta
D	5	.005"	.015"	.035"	.065"	Mo W coat
B	1	.020"	.035"	.082"	.125"	Ta

CALC. ERRORS: O - .020" WIRE, * - .005" WIRE