JUL 28 1965

MASTER

THERMOCOUPLE DEVELOPMENT FOR PROJECT ROVER

By

E. A. Brown, B. G. Goodier, J. E. Perry, Jr.
R. L. Petty, and W. R. Prince

University of California
Los Alamos Scientific Laboratory, *Univ. of California, N. Mex.*
Los Alamos, New Mexico

and

C. R. Tallman
Aerojet General Corporation
Azusa, California

ABSTRACT

Thermocouples are used for the control and diagnostic measurement of the thermal behavior of cores in the Kiwi and Nerva reactors of Project Rover. The predominant hostile environmental conditions are those of hot hydrogen, hot graphite, and intense nuclear radiation. W/W 26 Re thermocouples, insulated by BeO and encased in Mo or Ta sheaths, seem to show the most promise. Some aspects of thermocouple development, principally shunt effects and sheath integrity, are discussed.

I. INTRODUCTION

Project Rover seeks to achieve rocket propulsion through the use of a nuclear reactor to heat hydrogen propellant gas. In order to study the thermal behavior of the reactor core (i.e. heat exchanger) it is desirable to measure the graphite-uranium fuel temperatures at many locations simultaneously. Thermocouples appear to be the only practical way of doing this. The thermocouples have to withstand hydrogen and graphite at as high temperatures as possible, in the presence of a strong nuclear radiation flux. The thermocouples have lengths ranging up to 60" and diameters limited to about 1/8".

The thermocouples best able to stand the environment appear to be tungsten vs. tungsten 26% rhenium, insulated by BeO, and encased in a molybdenum or tantalum sheath. It is hoped ultimately to be able to measure temperatures in the vicinity of 5000°R ($\approx$ 2500°C) with errors no worse than a few percent.

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.

APPROVED FOR PUBLIC RELEASE

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.

The major problems encountered to date have been (a) shunt error and (b) sheath integrity.

Over a considerable range of temperature the resistivity of BeO decreases exponentially with temperature. Thus at sufficiently high temperatures the BeO shunt resistance between thermocouple wires becomes comparable with wire resistance, and the thermocouple output diverges from the theoretical Seebeck voltage. The discrepancy can be positive or negative. It depends on thermocouple geometry and longitudinal temperature distribution. A partial cure is to increase transverse dimensions of the thermocouple; an increased web of BeO produces increased insulation, and increased wire diameter reduces wire resistance relative to shunt resistance. A further improvement can come from cooling the thermocouple throughout most of its length and letting only the last few inches be at the fuel temperature.

The sheath problem appears to be far from a satisfactory solution. Molybdenum sheaths have failed through formation of a low-melting-point eutectic of Mo and Mo_2C . This allows formation of a new thermal junction at an indeterminate location, which combines with shunt effects to produce nearly meaningless results. Tantalum sheaths in hydrogen tend to be destroyed by the formation of tantalum hydride in the temperature range of approximately 750° to 2600°R . The successful use of tantalum depends entirely upon the use of a coating of material which is capable of keeping hydrogen away from the tantalum sheath. Some other sheath materials are considered possibly useful, but the applicable materials evaluation work will not be completed for some time.

This paper will describe principally the present status of development work related to the two major problems of shunting and sheath integrity. The lesser problems of radiation effects and differential thermal expansion will be mentioned. The symbol TC may be used occasionally hereinafter for thermocouple. Temperatures are expressed on the Rankine scale.

II. SHUNT EFFECTS

Shunt effects have been demonstrated experimentally and calculated theoretically. Because the dependence of shunt effects on various parameters is best elucidated by the calculations, they will be discussed first.

Digital Calculation of Shunt Effects

The aim of the digital calculation of the shunt effects was a qualitative understanding of the processes. Because of uncertainties in BeO resistivity and wire-to-insulator contact, it was considered impossible to describe the process quantitatively. The technique of computation was to convert the distributed parameters -- resistances and thermal emf's -- into lumped parameters for each inch of thermocouple length, and then to solve by matrix methods the many loop equations of the lumped model.

For an ideal thermocouple of materials A and B with cold junction at 32°F (= 492°R) and hot junction at temperature T°R, the output or Seebeck voltage is given by Eq. (1)¹:

$$(1) \quad H_{AB}(T) = \pi_{AB}(T) + \int_{492^{\circ}R}^T (\sigma_A - \sigma_B) dT.$$

The Peltier (junction) voltage is¹

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

The difference in Thomson (thermal gradient) coefficients for the two wires is given by¹:

$$(3) \quad \left(\sigma_A - \sigma_B \right)_T = -T \left(\frac{d^2 H_{AB}}{dT^2} \right)_T,$$

while the total contribution from the Thomson effect is the integral of this expression, as shown in Eq. (1).

The following data from Hoskins Manufacturing Co. were used for $H_{AB}(T)$: 460°R (= 0°F) ≤ T ≤ 4560°R (= 4100°F) adopted November 23, 1962, and 4452°R (= 3992°F) ≤ T ≤ 6072°R (= 5612°F) tentatively released on October 1, 1964.

To obtain the values of distributed thermal emf, the Hoskins data were fitted by a least squares code to a polynomial in T. From this, equations (2) and (3) were evaluated. In the least squares fitting, the 1962 data were given weight four, and the 1964 data weight one. The following fourth degree expression* describes the data:

* A sixth degree expression fits the data in the high temperature region somewhat more accurately than the fourth degree expression. However, the data are not believed accurate enough to warrant the extra complexity. The Peltier emf and Thomson coefficient derived from the sixth degree fit are considerably different from those derived from the fourth degree fit.

$$(4) \quad H_{AB}(T) = \sum_0^4 A_n T^n, \text{ where}$$

n	A_n
0	$-2.90129 \times 10^{-2},$
1	$1.67553 \times 10^{-3},$
2	$1.96982 \times 10^{-5},$
3	$-7.96850 \times 10^{-9}, \text{ and}$
4	$9.91660 \times 10^{-13}.$

For this fit the standard deviation was 0.12 mv and the largest single error in the 1962 data region was 10°R at 2750°R. In the 1964 data the largest error was 55°R at the highest temperature. These errors are well within the accuracy of the Hoskins data. Figure 1 shows the fit to the data*. The Seebeck emf, the Peltier emf, and the Thomson coefficient are given in Fig. 2.

The considerable difference between Seebeck and Peltier emf's is apparent in Fig. 2. Because of this difference it was decided to include both Thomson and Peltier effects in the shunt calculation, rather than assume a "distributed Seebeck effect" as had been done in other calculations³.

The principal calculational models are shown in Fig. 3, while some of the calculational details are given in Fig. 4. Thomson voltage is, of course, developed in both wires, as shown in Fig. 4a. However, only the differential Thomson voltage is given by Eq. (3), and this is used as shown in Fig. 4b. (Figures 4a and 4b are electrically identical.) Peltier emf's are shown in series with each shunt resistance. That these are required may be seen from reference to Fig. 4c in which R_{T1} and R_{T2} are variable resistors. If $R_{T1} \rightarrow 0$ and R_{T2} is large, the thermocouple reads temperature T_1 ; whereas $R_{T2} \rightarrow 0$ and R_{T1} large gives an indication of T_2 . $R_1 = R_2$ leads to an average temperature reading. -- The so-called "hot zone" error² requires a distributed Peltier emf since it can not be produced by the Thomson effect.

Initial values of BeO resistances were calculated by assuming full wire-to-BeO-to-sheath contact in the cross sectional sketch of Fig. 4d. Resistance paper models of the cross section served to provide some idea of the increase of BeO resistance caused by

*The temperature scale in Fig. 1 is in °C.

point contacts between metals and insulator. In some of the calculations the BeO resistance was varied from 1/10 to 10 times the full-contact value. In almost all calculations the three insulator web thicknesses, wire-to-sheath and wire-to-wire, were made equal, which corresponds to current manufacturing practice.

The assumed variation of BeO resistivity with temperature was constructed from three sets of data³, and is shown in Fig. 5. This appears to be a quite good representation up to the melting point at $\approx 5000^\circ\text{R}$.

Resistivities of W and W 26 Re vs. temperature were obtained from Hoskins⁴. Each of the metal curves was fitted by the least squares code to a power series in T.

The computations were performed on an IBM 7094 computer. In a typical case the temperature distribution along the TC was the primary input. From this, local emf's and local resistances were calculated per inch of length, and the loop equations of the one-inch lumps were solved by a SHARE matrix code.

Typical results are shown in Figs. 6 through 11.

In Fig. 6 the shunt error is plotted vs. insertion length for thermocouples whose junction is always at 4500°R . It is clear that in this case the shunt error is always a loss in output, and that this loss increases rapidly with insertion length. Further, as wire and insulator diameters decrease, progressing from curve A to curve D, the loss becomes more severe. This is a clear-cut case of shunt loss. The variation of shunt loss with insertion length and wire diameter seems reasonable: a 30" thermocouple has six times the series (wire) impedance and six times the shunt (BeO) conductance of a 5" thermocouple. Reduction of wire diameter enhances the adverse effects. (Note that the calculations extend only down to 2500°R which is below the point where shunting is important.)

Figure 7 shows cases where the shunt error is either positive or negative. Here all junctions are at 4500°R and all insertion lengths are 30", but four different temperature profiles are assumed. Consider first curve A for 0.030" wire diameter. Profile 1 has a short distance at high temperature and there is a small shunt loss. Profiles 2 and 3 have progressively longer hot regions and larger losses. However, the region above 4500°R in profile 4 makes the shunt error positive. This is a case of "hot zone error": evidently the effect of the distributed Peltier junction outweighs the shunt loss. -- Reference to curve D shows that the results are dependent on wire diameter. Here the shunt loss is progressively larger from profile 1 through 3. With profile 4 the shunt loss is

larger than the distributed-junction gain, so that the net error is still negative. -- Curve C has zero net error for profile 4. If one could calibrate the calculations properly, it should then be possible to construct a real thermocouple with zero error for this length and this temperature profile.

Figure 8 shows an example of hot zone calculations. Here the junction at 30" is maintained at 2500°R, while a section of thermocouple 1" or 10" long is heated to various higher temperatures. The shunt error is positive because of the distributed Peltier junction effect in the hot region. The error depends on the length and temperature of the hot section, and on wire and insulator size.

Of direct use in the Rover thermocouple development work were calculations like those of Fig. 9. There shunt error is plotted against wire diameter for a hypothetical reactor temperature distribution, with insulator diameter given parametrically. Generally the loss decreases as the wire and insulator sizes increase, with rapidly diminishing benefits for wires larger than 0.015" or 0.020". (The increase in shunt loss for 0.030" wire and 0.075" BeO is caused by the very thin insulator webs for this geometry.) As a result of these calculations 0.020" wires were chosen for the next generation of core thermocouples.

Some indication of the effect of varying BeO contact and resistivity was obtained from calculated losses shown in Fig. 10. Here a particular thermocouple geometry (0.005" wire, 0.035" insulator) was exposed to a single temperature distribution, and the loss calculated as a function of tip location. Full contact, wire-BeO-sheath, was assumed for the initial calculations (curve labeled 1.0). The resistance was then varied by factors up to 10 and down to 0.05, and the calculations repeated for each factor. The considerable variation of shunt loss with assumed BeO resistance is apparent in the figure. An attempt to determine an effective resistivity for BeO by comparing calculated and experimental losses is in progress.

It is clear that the shunt loss is reduced materially by having a short length of thermocouple exposed to high temperature. Figure 11 shows the calculated loss for several cases in which the temperature rises from 2500°R to the junction value in a distance of five inches.* Figure 12 shows a possible application of this technique in a Rover reactor: cooling gas flows along most of the length of a thermocouple and is diverted away at a point a few inches from the junction. It is necessary of course to show that longitudinal heat conduction does not decrease the tip temperature, and that the cooling gas does not perturb the temperature to be measured.

* For this case calculational increments were 0.5" long.

In closing this section a few additional facts are worth mentioning. (A) The simplified model of Fig. 3(c) produced results essentially identical with those of the full sheath model, Fig. 3(b), and was used for all the calculations presented here. (B) Gamma ray heating of the thermocouple wires can influence shunt errors in ways that are not easy to predict. Thus if wire-to-insulator contact is deliberately reduced to increase shunt resistance, wire temperature will rise considerably above sheath temperature. This may affect both the distributed Peltier effect and the shunt loss. It would be fairly easy to incorporate these calculations in the code, and this may be done. (C) It should be possible to derive empirical relations describing shunt effects in terms of the pertinent parameters for a given thermocouple application. These relations might then prove useful in predicting the change in reading accuracy for a given change in a parameter, or, hopefully, in calculating corrections to be applied to observed readings.

Experimental Measurement of Shunt Effects

There is a considerable body of local experimental data which confirms some aspects of the shunt effect.

The first evidence emerged during the high power run of the Rover reactor Kiwi-B-4D. It was observed that the measured axial temperature distribution in the core fell quite far below that predicted by calculations of heat transfer from the reactor fuel to the hydrogen coolant-propellant. Disassembly of the reactor showed that in several cases the Mo thermocouple sheaths had melted back to form new junctions at locations of lower temperature. It was also felt that shunting might be the cause of additional lowering of thermocouple output. These disturbing facts led to initiation of the shunt calculations discussed above, and to the furnace measurements to be described now.

An existing furnace with 32" working length was modified to accept standard core thermocouples. These were placed inside the axial holes of a graphite test rod which extended from one end of the furnace to the other. Surrounding the rod was a hollow cylindrical graphite tube, 32" long, 2" I.D., and 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 ports spaced at about 6" intervals along the length of the furnace. The line of sight proceeded through windows, through 1/4" holes in the radiator, to the graphite rod wall, and finally in 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 window corrections were applied. The furnace could be pressurized with H_2 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 min. Power and thermocouple output were recorded on continuous strip charts. At each plateau the junction temperature was measured by the optical pyrometer. Occasional temperature distributions were measured pyrometrically using all six ports. To help obtain consistent results a single observer made all pyrometer readings.

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

In Fig. 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" O.D.⁵. 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

* The spread in the data becomes much less when the wire resistance is decreased relative to the BeO resistance. Thus in Fig. 14 the data for 8" insertion are much more consistent than for 24" insertion, and in Fig. 15 the data are better for 0.020" wire than for 0.005" wire.

trends of the data are shown. As in Fig. 13 the error increases rapidly with junction temperature. As noted in Fig. 6, 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 sleeve diameter and wire center-to-center distance, which is corroborated by the calculated results given earlier in Fig. 9.

In the center of Fig. 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 Fig. 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 Fig. 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 Fig. 10 indicates 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 Fig. 5, 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.

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

Only fragmentary data have demonstrated the effect of the distributed Peltier junction. Three of the first thermocouples tried in the furnace were inserted to a depth of 30". Reference to Fig. 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. Clearly the experiment should be repeated with a better sheath material.

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. It would seem desirable to make hot zone measurements with temperature profiles resembling those found in Rover reactors, and then to compare these results with calculations.

III. SHEATH INTEGRITY

Several sheath materials have been tried in the attempt to find one which will survive in the reactor environment up to temperatures in the vicinity of 5000°R. The studies are far from complete, so that the material presented below represents only present status.

Molybdenum

Over sixty Mo sheathed thermocouples tested locally during the past few years have confirmed that the Mo-MoC₂ eutectic melting point is 4460° ± 50°R. Mo sheaths have been found to be carbided somewhat below this temperature. Migration of C through the sheath can result in destruction of thermocouple insulation through formation of CO₂ and Be. In a life test performed with junction at 4350°R (8" insertion) the output error increased from -100°R to -600°R in 30 minutes. Sheath walls were 0.011" thick and were found to be carbided. On the other hand two separate half hour runs at 3600°R and 3700°R (24" insertion) showed no drift or change in calibration.

If a coating can be found which will exclude carbon from the Mo sheaths, the useful range of these couples will be raised several hundred degrees. The San Fernando Laboratory deposited 0.005" coats of W on five Mo-sheathed couples for this purpose. These thermocouples failed at ≈ 4650°R, which is about 200°R above the temperature at which Mo-sheathed

couples usually fail. Additional Mo-sheathed thermocouples are being coated with W to do drift-versus-time studies at constant temperatures from 4000° to 4700°R.

Other approaches which are being tested to keep carbon from the Mo sheaths include (1) a flame-sprayed coating of Ta carbide and (2) lining the thermocouple mounting hole in the graphite with a sleeve of Ta carbide or Nb carbide.

74% Tungsten 26% Rhenium

Four W-26 Re-sheathed thermocouples were tested in hot hydrogen and carbon. Two were life-tested at 4500°R and two were run up in temperature to failure. During the life test the outputs fell off rapidly after 15 minutes to errors of $\approx 700^\circ\text{R}$ at 26 minutes. This degradation probably was due to excessive carbon migration through the sheaths. The temperatures of the two thermocouples tested to destruction were increased slowly to the failure value in about 30 minutes. Both couples failed at approximately 4500°R even though the carbon eutectic melting point is $\approx 4900^\circ\text{R}$. The sheath tip on one of them melted at 4750°R. The second couple did not show evidence of melting after being subjected to a maximum temperature of 4600°R.

75% Tungsten 25% Molybdenum

Two 0.065" dia. 8" long thermocouples operated up to $\approx 5350^\circ\text{R}$. The tips were rather badly cracked and swollen, but there was no adherence to the graphite support. Output seemed reliable up to about 4800°R. Except for the tip region ($\approx 1/4"$) the sheath turned a golden color and appeared to be in excellent mechanical condition. No deterioration of output was noted in a half-hour life test at $\approx 4500^\circ\text{R}$. Attempts to obtain more of this material in tubing form have not been successful.

Tantalum

The most serious objection to Ta is its tendency to hydride in the temperature range from $\approx 1000^\circ$ to 2600°R. No hydriding has occurred in the 6 thermocouples that have been tested in hot hydrogen and carbon; however, it is possible that the furnace fixture used in these tests partially excluded the hydrogen from the Ta sheaths. Other Ta material tests in carbon and hydrogen have produced essentially complete destruction of the Ta, which is in accord with expectations. The hydriding rate seems to be dependent on hydrogen pressure; relative concentrations of hydrocarbons and hydrogen at the sheath, and whether the hydrogen is stagnant or flowing. Although the situation is quite unclear at this time, it is generally thought that Ta-sheathed

thermocouples will not be satisfactory unless hydrogen is isolated from the sheaths. Coatings which are being tested for this purpose include (1) liquid-moly grease, (2) nitriding the Ta surface, (3) carbiding the Ta surface, and (4) vapor-deposited W.

Tantalum with 0.005" Vapor-Deposited W Outer Coat

Tests on several 0.065" W-coated-Ta-sheathed thermocouples indicate that they work well, even with recycling, if the W integrity is maintained. There is a tendency, however, for the W to crack at temperatures above $\approx 4000^{\circ}\text{R}$ because Ta expands more with temperature than W. An attempt is being made to avoid this problem by changing the W-deposition process. In the past, the W coating was done at $\approx 1100^{\circ}\text{R}$ by hydrogen reduction of tungsten hexafluoride. This process has two problems. First, the W tends to coat over the Ta without forming a strong diffused bond. Secondly, the large temperature change from the deposition temperature (1100°R) to the operating temperature (4000° to 5000°R) produces high stress in the W due to thermal expansion. These two problems usually cause W cracking. Tantalum sheaths are being coated now at $\approx 2200^{\circ}\text{R}$ by the decomposition of tungsten chloride. At this temperature a diffused unstressed bond is formed with the Ta. In addition, the difference between the deposition temperature and maximum temperature has been reduced by 1100°R . Test samples coated with the chloride process will be available in the near future.

90% Tantalum 10% Tungsten

A number of thermocouples with Ta 10 W sheaths have been tested. This material is considerably stronger than Ta, and there is some evidence that it does not hydride as readily. The Ta 10 W couples have performed somewhat better than Ta, but both have the same basic problems to some degree. The development work being done with Ta 10 W essentially is identical to that with Ta.

New Materials Developments

A basic materials program has been started with The San Fernando Laboratory to develop vapor-deposited sheaths of two or three materials. The approach is to deposit various combinations of W, Re, and Mo in either alloy form or in layers of pure metals. Some of the combinations offer considerable promise, but it may be several months before the materials work is completed.

Sheath Summary

Much remains to be learned about the chemical-metallurgical interaction of the various sheath materials with the hydrogen-graphite environment.

Despite the uncertainty about hydride formation, Mo, Ta, and Ta 10 W have been chosen for the second generation of core thermocouples (see below).

75 W 25 Mo has performed well on a very limited number of tests. It is considerably more expensive than Ta, and is not presently available commercially in tubing form.

74 W 26 Re with a W outer coat may have some promise and is still being considered.

Sheath test results are summarized in Table 1.

IV. PROPOSED THERMOCOUPLE DESIGNS

Several thermocouple designs have resulted from the studies outlined above. The basic features of the designs are (a) large wire and insulator size, (b) use of Mo and Ta for the sheath material, and (c) cooling the sheath throughout most of its length when possible.

Standard Thermocouple Design

The "standard" version of reactor core thermocouple is being purchased with about a dozen variations. In all cases wire size is 0.020", and the outside diameter is 0.110". Sheaths are Mo, Ta, Ta 10 W, or W. These may be used bare, carbided (in the Ta case), or coated with 0.005" W. In an attempt to decide whether swaging produces a more uniform and more calculable wire-to-BeO-to-sheath contact, some thermocouples will have crushable BeO insulators and will be swaged to size. The remainder will have hard-fired BeO insulators. Sheaths will be carefully cleaned internally before assembly, and thermocouples will be filled with He for better cooling of the wires. The thermocouples will be terminated in long swaged leads containing Cu wires and MgO insulation. The junction between thermocouple and swaged lead occurs in a region which is at $\approx 200^\circ\text{R}$, so that development of thermal emf is not a problem. At this junction there will be a wire-to-wire spring coupling to accommodate the differential thermal expansion between the sheath and the thermocouple wires.

Advanced Thermocouple Concepts

Figure 16 shows two advanced concepts for reactor core thermocouples. Each of these is to be cooled to within a few inches of its thermal junction. In the bifilar version insulators are shown staggered to increase inter-wire resistance. The coaxial version has no insulators at all in the tip region.

V. RADIATION LEVELS AND EFFECTS

Ultimately it is expected that the maximum dose rates to be experienced by the thermocouples will be $\approx 2.5 \times 10^{18}$ n_f/cm²-sec (E > 50 kev) or $\approx 2 \times 10^{18}$ Mev/cm²-sec and $\approx 2 \times 10^7$ rad/sec of gamma rays. The integrated doses will be $\approx 10^{20}$ n_fvt and $\approx 10^{11}$ rads of gammas. It is believed that these doses are not sufficient to affect materially the output of the thermocouples⁶. As with all parts of the reactor, the thermocouples would melt if not properly cooled.

Rough calculations and a test in the Omega West Reactor have shown that radiation contributions to the shunt effect, either through gaseous conduction or ionization in the BeO, should not be significant in comparison to the thermal shunt effect discussed above.

VI. FUTURE DESCRIPTION OF THERMOCOUPLE WORK

Many metallographical pictures of thermocouple cross sections are now available. These await study and correlation with furnace temperature-time data. It is planned to incorporate these results in a second version of this paper, presumably to be issued as a LA-MS report. More detailed descriptions of the furnace data and of the digital shunt effects code are also planned, presumably to be written as LA-MS reports.

Acknowledgements

Many members of groups CMB-3, CMB-6, N-1, N-2, N-3, N-4, and N-7, of the Los Alamos Scientific Laboratory have helped, and will continue to help, in the development of thermocouples for the Rover reactors.

References

1. Finch, Donald I., "Temperature, Its Measurement and Control in Science and Industry", 3, 1; C. M. Herzfeld editor-in-chief; Reinhold Publishing Co., New York (1962).
2. R. J. Freeman, "High Temperature Thermometry Seminar, Held October 1959", U.S.A.E.C. report TID-7586 (1960). Also G. A. Gilmour and G. Collier, Westinghouse Astronuclear Laboratory, Large, Pennsylvania, private communication (1964).
3. R. E. Long and H. Z. Schofield, "Reactor Handbook", 3, Chapter 1.3, A.E.C. Report AECD-3647 (1953).
J. A. McGurty and W. C. Kuhlman, General Electric Co., Flight Propulsion Laboratory Dept., Cincinnati 15, Ohio. Report number TM-62-4-2, unpublished (1962).
W. R. Prince, Los Alamos Scientific Laboratory, Los Alamos, New Mexico, unpublished data (1964).
4. Technical Data Sheets originated by Hoskins Manufacturing Co., 445 Lawton Ave., Detroit 8, Michigan, unpublished.
5. All thermocouples of 0.065" O.D. sheath mentioned in this paper were produced by Aero Research Instrument Co., Inc. Division of American Standards, 315 N Aberdeen St., Chicago 7, Illinois.
6. W. E. Browning and C. E. Miller, P. 271, and Kelly, Johnson, and Baumann, p. 265. Temperature, Its Measurement and Control in Science and Industry, 3, C. M. Herzfeld, editor-in-chief; Reinhold Publishing Co., New York (1962).
7. W Coat on WANL Thermocouples supplied by Wheaton Industries, Inc., 422 Interstate Road, Addison, Illinois.

Table 1
Sheath Test Summary

Half Hour Life Test

Sheath	Wire Dia Mil	Sheath Dia Mil	Insertion in.	No. Run	Max JCT Temp °R	Max Cred Temp °R	Comments	No. Run	Insert Length	Temp °R	Comments
Mo	5	65	24	60	4460		Mo-MoC ₂ Eut. 4460°	1	8	4350	Error -100° to -600°
	20	125	24	1	4460						
Mo + W Coat	5	65	24	5	≈ 4750	≈ 4650	Sheath carbided melting observed	0			Not run
74W26Re	5	65	8	2	4750	4600	First Eut. 4900° but melting observed above 4750°R	1	8	4500	Error increased by 700° in 26 min.
75W25Mo	5	65	8	2	≈ 5100	4800	Tip swelled, rest of sheath good cond.	1	8	4500	Output steady
Ta	10	65	24	1	5150	4225	No hydride seen	0			Not run
	20	125	24	1	4820	4510	Ta-Ta ₂ Eut. 5600				
Ta + W Coat	5	65	8	2	5100	4750	Jct intact. No TaH _x .	1	8	4450	Output steady

Table 1 (Continued)

							Half Hour Life Test				
Sheath	Wire Dia Mil	Sheath Dia Mil	Insertion in.	No. Run	Max JCT Temp °R	Max Cred Temp °R	Comments	No. Run	Insert Length	Temp °R	Comments
Ta + W Coat	5	65	8	2	5300	4750	Tip swollen. No TaH _x				
	20	110	14	1	3 runs 2800 3000 4300	2800 3000 4300	Good Good Sheath disinte- grated while lowering temp. ^U				
	20	110	14	1	4300		Sheath disinte- grated while lowering temp.				
	5	65	8	2	5150	4700	He tip swollen	1	8	4450	Output steady
				1	5300	4700	H ₂ tip swollen No hydride				
90Ta10W + W Coat	5	65	8	2	5000	4700	H ₂ . No TaH _x	1	8	4450	Output steady

SEEBECK EMF
26 RE/W (mV)

DEGREE OF FIT = 4 TEMPERATURE (DEG C)

FIGURE 3 THERMOCOUPLE CALCULATION MODELS

FIGURE 8
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 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 12, COOLED THERMOCOUPLE INSTALLATION

FIGURE 14
THERMOCOUPLE SHUNT ERROR
VERSUS JUNCTION TEMPERATURE
WIRE DIA. = 0.005"

	BeO DIA	WIRE C TO C
LASL	0.035"	0.015"
WANL	0.024"	0.008"
CURVE	NUMBER OF TC's	
A	5	
B	4	
C	7	
D	5	
E	4

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

TC CHARACTERISTICS						
	No.	WIRE DIA.	WIRE ℄ TO ℄	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 Wcoat
B	1	.020"	.035"	.082"	.125"	Ta

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

FIGURE 16, ADVANCED THERMOCOUPLE CONCEPTS