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High-Temperature Reactor Core
Thermocouple Experiments

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High-Temperature Reactor Core
Thermocouple Experiments

by

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ABSTRACT

The combination of environment and required thermocouple location imposes definite limitations as to the temperature level and accuracy of thermocouple measurements in the Kiwi reactor cores. The thermocouples are required to operate in a hostile environment deep in the reactor core: in hot hydrogen, in direct contact with graphite, and under intense nuclear radiation. Experimental measurements of temperatures up to 4800°F using both prototype and actual reactor hardware thermocouples have been made under simulated reactor environment (no irradiation) in an electric resistance furnace. Results have indicated that the upper limit for the conventional operation of thermocouples in graphite reactor cores is restricted by the metal-carbon eutectic melting of the sheath. Errors in the indicated signal, depending upon the type and geometry of the thermocouple and length exposed to high temperature, can be as much as 1500°F at a true temperature of 4500°F due to excessive leakage currents between the wires. An acceptable thermocouple, as determined by maximum allowable operating temperature and lowest signal error, was a 1/8-inch-diameter tantalum sheathed thermocouple having swaged beryllium oxide insulators and 20-mil W-W26Re wires. Calculations indicate that additional errors in local temperature measurements are also possible as a result of the nuclear heating of the thermocouple assembly.

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INTRODUCTION

Recent Kiwi reactor tests in which relatively long power holds were scheduled have served to point up the need for a better understanding of in-core temperature measurements. In theory, the measurement of reactor core temperature can be achieved by many and varied methods: radiation devices, sonic sensors, thermocouples, etc. The environment, including the location of the material whose temperature is desired, dictates to a great extent the type of measuring device which can be used. Thermocouples are used to provide direct temperature measurements in the Kiwi reactor cores. The thermocouples operate in a hostile environment deep in the reactor core: in hot hydrogen, in direct contact with graphite, and under intense nuclear radiation. Access for the thermocouples is provided by axial channels in the core at various core radii. The core thermocouples used in recent Kiwi tests consisted of 5-mil W-W26Re wires, insulated with beryllium oxide insulators and protected by a 65-mil-diameter molybdenum metal sheath.

The thermocouple, in concept, provides the simplest and most direct high-temperature measurement. However, with the use of thermocouples in a reactor core, it was realized that somewhat new and unique problems in high-temperature thermometry would result. The magnitude of such problems had not been demonstrated prior to the actual Kiwi tests. These problem areas will be discussed in this paper and are indicated in schematic form in Figure 1. The first problem relates to the inability

of the thermocouple to measure actual temperature. Agreement exists between predicted temperature and actual measurements only up to temperatures of the order of 3000°F. At higher temperatures the measured values are lower than the predicted - the higher the predicted temperature the greater the error. The other problem is "burn-out" (melting) of the thermocouples with loss of reliable signal.

In an effort to explore these phenomena of thermocouple error and burn-out, an experimental program was initiated at LASL in which over one hundred refractory thermocouples were investigated in an electric resistance furnace. Both prototype and actual Kiwi hardware were evaluated under simulated reactor environment (no irradiation) at temperatures, in some cases, up to 4800°F.

FACILITIES AND TESTS

In order to simulate reactor environment, a long length of the thermocouple sheath was required to be in contact with high-temperature graphite and exposed to hydrogen. A schematic of the laboratory test set-up is shown in Figure 2. The thermal source was provided by a suitably designed hollow, tapered wall, resistance-heated, graphite radiator. Electrical power was supplied from storage batteries. The thermocouples were inserted into a graphite rod which in turn was inserted coaxially into the radiator. Desired axial temperature gradient and temperature level were obtained by adjusting both the insertion length of the thermocouple and the power-input to the radiator. Heating rates could be varied up to the order of 300 degrees per second. Temperature measurements were obtained by monitoring the thermocouple tip (junction) with a calibrated optical pyrometer. Thermocouple output was recorded on null-type continuous trace potentiometers. A photograph of the furnace is shown in Figure 3. Typical furnace axial temperature profiles are shown for several different power levels in Figure 4.

DESCRIPTION OF THERMOCOUPLES

The following table presents a listing of the various types of W-W26Re thermocouples tested during the experimental program.

SHEATH		INSULATOR		WIRE	
Material	Dia, in.	Material	Type	Dia, in.	Junction
Mo	0.065	BeO	Vitrified	0.005	Grounded
Mo	0.125	BeO	Vitrified	0.020	Grounded
Mo*	0.065	BeO	Vitrified	0.005	Grounded
W26Re	0.065	BeO	Vitrified	0.005	Grounded
W26Re	0.065	ThO ₂	Vitrified	0.005	Grounded
90Ta10W	0.065	BeO	Vitrified	0.005	Grounded
90Ta10W	0.065	BeO	Vitrified	0.005	Isolated
90Ta10W*	0.065	BeO	Vitrified	0.005	Grounded
75W25Mo	0.065	BeO	Vitrified	0.005	Grounded
Ta	0.065	BeO	Swaged	0.010	Isolated
Ta	0.065	ThO ₂	Swaged	0.010	Isolated
Ta	0.125	BeO	Vitrified	0.020	Isolated
Ta	0.125	ThO ₂	Vitrified	0.020	Isolated
Ta	0.125	BeO	Swaged	0.020	Isolated
Ta*	0.065	BeO	Vitrified	0.005	Grounded

* W vapor deposited

TECHNICAL DISCUSSION

The thermocouple research carried out during this program was concerned with investigations of the accuracy and the limitations to reliable thermocouple measurements under simulated reactor conditions.

Signal Error

Shunting - At the onset of the experiments it was strongly suspected that a major cause of the thermocouple error was due to breakdown of the electrical resistance of the insulator at high temperatures. A brief series of tests was performed in a small 5-KW induction furnace to attempt to evaluate the leakage between wires in two-hole refractory oxide thermocouple insulators. Some experimental results showing the trend of the degradation of electrical resistance with temperature for two typical thermocouple insulator materials is illustrated in Figure 5. High-temperature resistance measurements are subject to a variety of errors, and consequently these results are presented only to show trends and are not intended as precise resistivity data. Insulation failure would provide a low resistance path between the wires such that the thermocouple junction emf would be shunted and indicate a lower voltage at the instrument readout. It should be pointed out that for the insulator geometry investigated, a similar leakage existed between the wires and the sheath.

Experiments confirmed the lowering of the thermocouple output; the junction shunting was found to be a function of the temperature gradient and level, the length of thermocouple exposed to high temperature, and the type and geometry of the thermocouple. Typical experimental results are presented in Figure 6 for several different thermocouples. The data are plotted as the indicated error versus the actual (optical) junction temperature. The onset of the error is seen to be at about 3000°F. Errors of 1500°F in the indicated signal were measured at true temperatures of 4500°F. Shunting is primarily a function of the ratio of the resistance of the wires to the resistance of the insulator - the lower the ratio the lower the shunting. Consequently, the errors were lowest for the thermocouples with 0.020-inch wires and beryllium oxide insulators. Typical signal error for 20-mil W-W26Re wire, tantalum sheathed, beryllium oxide insulated thermocouple was of the order of

100°F at a true temperature of 4000°F. The error for the same thermocouple was 400°F at a true temperature of 4500°F.

It was assumed that the Kiwi thermocouples would perform for limited periods of time up to about their metal-carbon eutectic melt point. The experimental results from thermocouples (Mo and W26Re), whose exposure temperature exceeded the metal-carbon eutectic, confirmed that the maximum thermocouple signal was invariably limited to the carbon eutectic melt of the sheath material.

The ability for the tantalum sheathed thermocouples to operate successfully in hydrogen has been demonstrated in furnace tests of over a dozen tantalum sheathed thermocouples. It is an established fact that tantalum will absorb hydrogen at a decreasing rate over a temperature range from about 300 to 2000°F with resulting destructive embrittlement of the tantalum. However, such has not been the case when the tantalum thermocouples were run in both hydrogen and carbon atmosphere. Repeated heating of the tantalum sheathed thermocouples over the embrittlement temperature range did not result in the above mentioned destructive embrittlement. Following high-temperature exposure the thermocouples showed the gold coloration indicative of carbide formation. One possible explanation for the fact that destructive embrittlement was not experienced when tantalum was heated in the presence of both hydrogen and carbon is the difference in transport mechanism when both environments are present. Hydrogen, reportedly a good carrier of carbon, could have accelerated the formation of a thin carbide skin on the tantalum which in turn would retard the diffusion of hydrogen into the tantalum. In the case of molybdenum thermocouples the presence of carbon proved to be a disadvantage; in the case of tantalum it appears that the presence of carbon can be used advantageously.

Drift - Future reactor requirements call for relatively long operational periods. Consequently time-temperature thermocouple performance was investigated and found to be another source of signal error for some types of thermocouples. Experiments have indicated that exposures

of about 30 minutes at temperatures of the order of 4000°F will cause molybdenum and W26Re sheathed thermocouples to drift intolerably. However, 75W25Mo, 90Ta10W, and tantalum sheathed thermocouples are stable for long time exposure. Typical drift results showing the magnitude of the thermocouple error as a function of time are presented in Figure 7. The signal drift with time for the W26Re and molybdenum sheathed thermocouples suggests possible carbon diffusion through the sheath and contamination of the wires with a corresponding shift in their emf versus temperature characteristics. The magnitude of the error for the W26Re and molybdenum is a function therefore of not only electrical signal shunting due to insulator breakdown, but also to change in emf versus temperature calibration of the wires.

Nuclear Radiation - The signal errors previously discussed concerned furnace tests in which equilibrium conditions exist (at a given cross section) in the thermocouple body; i.e., $T_{\text{wires}} = T_{\text{insul}} = T_{\text{sheath}} = T_{\text{graphite}}$. In the reactor environment due to neutron and gamma heating $T_{\text{wire}} > T_{\text{insul}} > T_{\text{sheath}} > T_{\text{graphite}}$. Therefore it is estimated that additional depression of the thermocouple read-out did occur during reactor operation as a result of the estimated higher temperatures within the thermocouple body.

Irradiation for short times (about 30 minutes) should not produce measurable effects in either the wires in the thermocouple circuit or in the insulators. Irradiation of any air within the thermocouple body will tend to ionize the air with an effect probably so small that it cannot be detected.

Estimated temperatures which could exist inside a typical thermocouple body during reactor operation are shown schematically in Figure 8. The temperature levels are a sensitive function of the thermal resistance between the thermocouple wires and the surroundings - the large temperature drops occur across the annular gaps filled with gas. The elimination of the gaps both inside the thermocouple body and

between the sheath and the graphite would greatly reduce any thermocouple error resulting from the radiation environment. Swaging of the thermocouple assembly, in the case of ductile sheath material, could remove the gaps inside the thermocouple; and "potting" or mechanical fit could minimize the clearance between the sheath and the surrounding material. This potting of the thermocouple would also reduce any interstitial gas leakage down the thermocouple channel and thus remove another uncertainty in the estimation of the temperature distribution in the thermocouple assembly.

CONCLUSIONS

The results of the high-temperature reactor core thermocouple experimental program have indicated that:

1. The combination of environment and required thermocouple location impose definite limitations as to the temperature level and accuracy of thermocouple measurements in the Kiwi reactor cores.
2. The upper limit for the conventional operation of thermocouples in graphite reactor cores is restricted by the metal-carbon eutectic melting of the sheath.
3. Signal errors as a result of excessive leakage currents in the thermocouple assembly have been measured up to 1500°F at true temperatures of 4500°F, depending upon the type and length of thermocouple exposed to high temperature.
4. An acceptable thermocouple, as determined by maximum allowable operating temperature and lowest signal error, was a 1/8-inch-diameter tantalum sheathed thermocouple having swaged beryllium oxide insulators and 20-mil W-W26Re wires.
5. Removal of the annular gaps filled with gas both inside the thermocouple body and between the thermocouple sheath and surrounding core material will greatly reduce any signal errors resulting from nuclear heating of the thermocouple assembly.

Figure 1 Schematic of Reactor Core Temperature Profile

Figure 2 Schematic of Laboratory Test Set-up

Figure 3 Thermocouple Test Facility

Figure 4 Typical Furnace Temperature Profiles

Figure 5 Resistance Measurements of Typical Thermocouple Insulators

Figure 6 Shunting Characteristics, W-W26Re Thermocouples

Figure 7 Drift Characteristics, W-W26Re Thermocouples

Figure 8 Estimated Temperature Inside Thermocouple During Reactor Operation