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Argonne National Laboratory

FARET IN-CORE INSTRUMENT DEVELOPMENT

by

Glenn F. Popper and Alvin E. Knox

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Printed in the United States of America

Available from

Clearinghouse for Federal Scientific and Technical Information
National Bureau of Standards, U. S. Department of Commerce
Springfield, Virginia 22151

Price: Printed Copy \$3.00; Microfiche \$0.65

ANL-7161

Instruments (TID-4500)

AEC Research and
Development Report

CFSTI PRICES

ARGONNE NATIONAL LABORATORY

9700 South Cass Avenue

Argonne, Illinois 60439

H.C. \$3.00; MN .65

FARET IN-CORE INSTRUMENT DEVELOPMENT

by

Glenn F. Popper and Alvin E. Knox

Reactor Engineering Division

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July 1966

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FARET IN-CORE INSTRUMENT DEVELOPMENT

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I. INTRODUCTION

A. Objectives

The FARET experimental program^{1,2} required special in-core instruments, particularly for the measurement of fuel-pin and coolant temperatures, coolant flow rates in fuel-element assemblies, fission gas buildup pressure in the fuel pins, and neutron and gamma fluxes. These instruments were in addition to those required for normal plant operation.

FARET was to have been a 50-MW(t) sodium-cooled fast reactor experimental facility³ having the following features: 1) the capability to irradiate a broad variety of fuels over a wide range of operating conditions, 2) the ability to permit simultaneous experimental irradiation of large numbers of different fuel elements under conditions analogous to those achievable in experimental loops, 3) the capability to provide instruments within the reactor core to measure the important irradiation parameters, 4) the broad flexibility in operating temperature, flow rate, neutron flux and power density to permit achieving operating conditions comparable to those that would be encountered in power reactors of the future, and 5) the wide latitude in experimental loading to allow experiments to be conducted for the determination of operating parameters related to stability and safety of fast power reactors.

A particularly important design objective was the provision for instrumenting in-reactor components. The FARET design permitted instrumented subassemblies and other components to be installed in the reactor vessel, as shown in Fig. I.1. Provisions for bringing the in-core-instrument leads out of the vessel and cell to appropriate readout locations in the plant were incorporated. Mechanical connectors for use in a 1200°F sodium-vapor environment were being developed to facilitate the installation and removal of instrumented subassemblies.

The accurate measurement of fuel-pin temperatures as high as 2760°C, which is the melting point of UO₂, was one of the instrument objectives. The performance of materials at these high temperatures was uncertain. Tests were conducted to determine the temperature-emf characteristics of the selected thermocouple combinations as well as other material properties. Investigations included a study of the compatibility of the sensor materials with the fuels, stability of the sensors

Fig. I.1. Reactor Vessel and Cavity Assembly

after temperature cycling and irradiation, and irradiation effects on the sensor materials. When the final material selections would have been made, actual prototype thermocouples would have been calibrated and tested.

By measuring the differential temperature across the fuel elements and the flow rate through them, local power of a fuel element could be computed. To accomplish this, tests and investigations similar to those described above were being carried out for thermocouples that would be used to measure coolant temperatures. Several different types of sodium flowmeters were being investigated, developed, and tested.

Dry thimbles were to be provided in instrumented fuel elements for nuclear detectors (wires, foils, ion chambers, etc.). A commercially available drive system was to be adapted for this use.

Pressure and linear-displacement transducers to be used to measure buildup of pressure in a fuel pin and fuel displacement were also to be studied and developed.

One proposed scheme for extracting the large number of signals from in-core instruments from the core required an electrical connector located at the top of an instrumented fuel assembly. The connector must be capable of withstanding the high-temperature (650°C) and nuclear-radiation environment above the core, and must be sealed from the sodium or sodium-vapor environment in order to prevent short circuits. Electrical connectors and mechanical seals were being extensively tested for this application. A flexible lead wire and pressure-tube assembly was also being developed. Alternative all-welded connector designs were considered as a backup approach if the mechanically sealed connector design could not be developed in time.

B. Design Criteria

The operating capability of the principal FARET process systems permitted a wide range of reactor conditions to be achieved. At a mixed-mean sodium outlet temperature of 790°F from the reactor vessel, the maximum capability for reactor power was 50 MW(t). At the maximum permissible sodium outlet temperature from the vessel, 1150°F, a somewhat greater power capability was available due to the greater temperature differences across the heat exchangers. The coolant inlet temperature to the reactor could have been controlled over the range from 600°F to 960°F. The reactor was designed for a maximum permissible rise of coolant temperature across the core of 240°F; local temperature rises in individual subassemblies could have been larger, if necessary, with coolant outlet temperatures from a subassembly of 1300°F or greater. At full-power and maximum-temperature conditions, a mixed-mean core coolant outlet

temperature of 1200°F would be achieved and a mixed-mean reactor vessel coolant outlet temperature of 1150°F was to be maintained by tempering the core coolant outlet temperature with coolant bypassed around the core.

A maximum flow rate of 7500 gpm of coolant was provided at core pressure drops of up to 80 psi. At maximum core coolant outlet conditions, 1200°F, 6000 gpm flows through the core and 1500 gpm is bypassed to the mixing chamber at the core outlet. The coolant flow rate can be controlled over the range from 10 to 100 percent for cores with pressure drops ranging from 40 to 80 psi at rated flow.

A primary design objective was to provide a capability to perform a wide variety of experiments even though the experimental requirements were not clearly defined or not even possibly known. The vessel arrangement readily permitted the assembly of core configurations up to 500 liters, with a core height of 3 ft or greater. Within the subassembly configuration, various fuel-element or other test-component arrangements could be utilized. Control of coolant flow rate to a subassembly was provided by fixed orifices in the lower-end fitting of a subassembly, thereby permitting a predetermined flow rate in each subassembly. An arrangement of 12 control rods was provided initially. Different arrangements of control rods and drives could be used, if desired.

One of the more important capabilities of the facility was the degree of freedom for access to the core for instrumentation of in-core components. The reactor vessel extension contained penetrations for the leads from all in-core devices, such as instrumented subassemblies and re-entrant loops. Penetrations in the cell walls and floors permitted the leads to be brought through the containment structure, and space was provided for cable trays and terminal boards for up to 1200 pairs of thermocouple leads, 200 coaxial cable leads, and 300 shielded copper conductors. In addition, a 15-ft-long panel-board space was provided in the control room for installing instruments to measure, record, control, etc., the signals. An important link in this chain was the connection of the lead wires to the subassembly within the vessel. It was believed that this could be accomplished by a mechanically coupled connector. This was recognized as a difficult development since the connector must operate in a sodium environment at 1200°F.

Since it was desirable to monitor temperatures, fission gas release, and coolant flow rate in the test subassemblies, instruments for these purposes were under development. Although this was a difficult and challenging area of research, the results were encouraging. Also, developments in other fields and other programs would have contributed to the solution of these problems. The remainder of this report contains the results of the program to develop in-core instruments for FARET. For clarity, a typical instrumented fuel element is shown in Fig. I.2.

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Fig. I.2. Instrumented Core Subassembly

II. INSTRUMENT DEVELOPMENT

A. Fuel-pin Thermocouples

1. Introduction

It was anticipated that certain phases of the Fast Reactor Test (FARET) program would require sensors to measure fuel-pin temperatures as high as 2760°C , the melting point of UO_2 . Resistance thermometers, gas-expansion devices, and thermocouples were initially considered. Even the possibility of using a thermionic diode was briefly explored. Although gas-expansion devices looked attractive, thermocouples appeared to be the best-suited sensors for this particular application.

Thermocouples were selected because they were small in size and, therefore, could be installed in the rather small-diameter fuel pins. The small size and, hence, mass of the sensor would also contribute to a better time response, which would be important if transfer-function type experiments are desired. Finally, only electrical leads need penetrate the reactor vessel.

High-temperature thermocouples are limited for use in surroundings that will not affect their thermoelectric output. For most applications, a sheathed construction is needed. The sheath metal must be compatible with the fuel material, atmosphere, and insulator over the thermocouple wire. Otherwise, solid-phase reactions can proceed at extremely rapid rates, thereby destroying the sensor. The thermocouple wires must be compatible with their electrical insulator for the same reason. The refractory oxide which is used as an electrical insulator must have a high electrical resistivity at the operating temperature. Otherwise, the insulator will act as a shunt, possibly causing erroneous readings known as "hot zone" errors. These hot-zone errors will now be analyzed.

2. Analysis for Hot-zone Errors

When thermocouples insulated by refractory oxides are used to measure temperatures in the range from 1000 to 2800°C , a phenomenon described as the "distributed Seebeck battery"⁴ must be considered. These distributed voltage sources coupled with a leaky cable usually introduce errors in the measurement.

These so-called hot-zone errors can be determined when the thermocouple is treated as a d.c. transmission line having a generator (hot junction) with some internal resistance as a source, distributed series and shunting components of resistance along its length, distributed voltage sources along its length, and an infinite impedance load across the receiving end at null balance. Figure II.1 shows the equivalent circuit of a thermocouple.

Fig. II.1
Equivalent Circuit of
a Thermocouple

The differential equations for this circuit can be shown to be

$$-\frac{dv}{dx} = R(x) i; \quad (1)$$

$$-\frac{di}{dx} = \frac{v - v_g(x)}{G(x)} \quad (2)$$

where

v is the voltage at the point x ;

$R(x)$ is the wire resistance per unit length of line at x ;

$G(x)$ is the insulation resistance of unit length of line at x ;

$v_g(x)$ is the distributed voltage source along the line at x .

Combination of Eqs. (1) and (2) yields

$$\frac{d^2v}{dx^2} - \frac{dR(x)}{dx} \frac{1}{R(x)} \frac{dv}{dx} - \frac{R(x)}{G(x)} v + \frac{v_g(x) R(x)}{G(x)} = 0, \quad (3)$$

which can be reduced to two first-order equations. Let

$$y_2 = \frac{dv}{dx} \quad (4)$$

and

$$y_1 = v. \quad (5)$$

By means of Eqs. (3), (4), and (5), we obtain

$$\frac{dy_1}{dx} = y_2 = f_1 \quad (6)$$

and

$$\frac{dy_2}{dx} = \frac{dR(x)}{dx} \frac{1}{R(x)} y_2 + \frac{R(x)}{G(x)} [y_1 - v_g(x)] = f_2, \quad (7)$$

where f_1 and f_2 are different functions.

Equations (6) and (7) have been programmed for numerical solution by a digital computer using the Kutta-Merson Method.^{5,6} The quantities $R(x)$, $G(x)$, and $v_g(x)$ are determined by the temperature distribution along the line, and from the physical properties and dimensions of the thermocouple materials; these quantities can be of any form. For this case, R_g is zero. The only complication is that this analysis results in a two-point boundary-value problem. The initial (hot junction) value V_t of the voltage (v) is given, and the final value of the slope $\left. \frac{dv}{dx} \right|_L$ must be made zero.

Because of the two-point boundary values, an iteration process must be used to find the final value of the voltage and hence the indicated temperature. This results in a longer than normal computation time.

Coaxial (see Fig. II.2a) and two-conductor (see Fig. II.2b) thermocouple cables have been analyzed.

The resistivity of most metals can be expressed as a function of temperature t

$$\rho_w(t) = k_1 + k_2 t + k_3 t^2, \quad (8)$$

where k_1 , k_2 , and k_3 are constants determined from empirical resistivity curves or standard tables. The constants which are needed to determine

Fig. II.2. Thermocouple Cables

the resistivity of some thermocouple materials are listed in Table 1. These constants, along with those presented in Table 3, have been

TABLE 1. Constants for Wire Resistivity-Temperature Equation

$$\rho_w = k_1 + k_2 t + k_3 t^2$$

Material	k_1 , $\Omega\text{-cm}$ $\times 10^{-6}$	k_2 , $\Omega\text{-cm/deg}$ $\times 10^{-8}$	k_3 , $\Omega\text{-cm/deg}^2$ $\times 10^{-12}$	Accuracy, %	Temperature Range, °C	References
W	4.93	2.60	2.24	1.0	20-3000	7, 8
Re	19.33	7.05	-13.73	8.0	20-2400	7
W-3% Re	7.57	2.56	2.57	9.0	20-2800	9
W-5% Re	17.69	1.55	5.84	1.0	20-2000	8
W-25% Re	29.82	2.45	1.62	3.0	20-2800	10
W-26% Re	30.59	2.06	3.79	1.0	20-2000	8
Pt	7.83	3.92	-5.79	1.0	20-1500	7
Pt-10% Rh	18.43	3.09	-3.21	1.0	20-1500	7
Pt-13% Rh	19.02	2.97	-2.82	1.0	20-1500	7
Chromel P	70.22	2.66	-3.95	1.0	20-1100	7
Alumel	29.93	4.55	-14.41	6.0	20-1100	7
Iron	8.93	4.02	95.89	5.0	20-800	7
Constantan	48.82	-0.21	6.69	0.5	20-1100	7

determined by least-square fitting the data given in the references cited. The listed accuracy is the greatest deviation from the data points over the stated temperature range.

The total resistance $R(t)$ per unit length of coaxial line is given by

$$R(t) = \frac{4\rho_{cw}(t)}{\pi D_1^2} + \frac{4\rho_s(t)}{\pi(D_3^2 - D_2^2)} \quad (9a)$$

where

$\rho_{cw}(t)$ is the resistivity of the central wire;

$\rho_s(t)$ is the resistivity of the sheath material;

D_1 , D_2 , and D_3 are as shown in Fig. II.2.

For the two-conductor cable, Eq. (9a) becomes

$$R(t) = \frac{4}{\pi D_1^2} [\rho_{w1}(t) + \rho_{w2}(t)], \quad (9b)$$

where

$\rho_{w1}(t)$ is the resistivity of one of the wires;

$\rho_{w2}(t)$ is the resistivity of the other.

The resistivity $\rho_i(t)$ of the insulating material was expressed as

$$\rho_i(t) = k_4 e^{k_5 t} + k_6 e^{k_7 t}, \quad (10)$$

where k_4 , k_5 , and k_7 are constants determined from empirical data. Some of the constants for the more common refractory oxides are listed in Table 2.

TABLE 2. Constants for Insulation Resistivity-Temperature Equation

$$\rho_i = k_4 e^{k_5 t} + k_6 e^{k_7 t}$$

Material	k_4 , $\Omega\text{-cm}$	k_5 , deg^{-1} $\times 10^{-3}$	k_6 , $\Omega\text{-cm}$	k_7 , deg^{-1} $\times 10^{-3}$	References
Zirconia	1×10^9	-16.60	1×10^3	-3.71	11-16
Magnesia	6×10^{15}	-20.7	1×10^8	-7.16	12-19
Alumina	1×10^{16}	-23.0	1×10^9	-8.06	12-18, 20
Beryllia	1×10^{17}	-23.0	1×10^{11}	-9.72	15-17, 20, 21
Thoria	7×10^9	-11.5	1×10^6	-3.00	15, 20, 22-28*

*Also private communication, Zirconium Corporation, Sept 1964.

The expressions for the insulation resistance of a unit length of cable were derived by the use of Gauss' flux theorem. For the coaxial cable shown in Fig. II.2a, the resistance between the center wire and the sheath becomes

$$G(t) = \frac{\rho_i(t)}{2\pi} \ln \left(\frac{D_2}{D_1} \right). \quad (11a)$$

For the two-wire thermocouple cable shown in Fig. II.2b, the insulation resistance between wires for a unit length of cable was obtained by assuming $D_1 \ll D_2$. This assumption is valid for the cases under consideration, and the resistance becomes

$$G(t) = \frac{\rho_i(t)}{\pi} \ln \left[\frac{2S(D_2^2 - S^2)}{D_1(D_2^2 + S^2)} \right]. \quad (11b)$$

The equation which expresses the emf generated by the thermocouple wire as a function of temperature was written as

$$V_g(t) = t(k_8 + k_9t + k_{10}t^2), \quad (12)$$

where k_8 , k_9 , and k_{10} are constants determined from emf-temperature tables. These constants are listed in Table 3 for various thermocouple combinations.

TABLE 3. Constants for Emf-Temperature Equation

Thermocouple Combination	$V_g = t(k_8 + k_9t + k_{10}t^2)$			Accuracy, %	Temperature Range, °C	Reference
	$k_8, \text{ V/deg}$ $\times 10^{-8}$	$k_9, \text{ V/deg}^2$ $\times 10^{-9}$	$k_{10}, \text{ V/deg}^3$ $\times 10^{-12}$			
W/Re	5.47	15.42	-5.51	26	100-2200	7
	7.85	11.60	-4.17	4	400-2200	
	9.34	9.50	-3.49	2	700-2200	
	10.64	7.88	-3.00	0.8	1000-2200	
W/W-26% Re	2.23	16.47	-4.48	12	100-2300	8
	3.25	14.92	-3.96	4.5	400-2300	
	4.58	13.12	-3.40	1.6	700-2300	
	5.87	11.54	-2.95	0.5	1000-2300	
W-3% Re/W-25% Re	11.63	9.59	-3.16	9.7	100-2400	29
	13.34	7.05	-2.34	3.1	400-2400	
	14.60	5.41	-1.85	0.8	700-2400	
	15.31	4.56	-1.61	0.2	1000-2400	
W-5% Re/W-26% Re	14.12	6.38	-2.50	6.6	100-2300	8
	15.66	4.01	-1.70	2.1	400-2300	
	16.82	2.44	-1.21	0.9	700-2300	
	17.88	1.15	-0.84	0.4	1000-2300	
Pt/Pt-10% Rh	6.27	4.73	-1.34	4.7	100-1700	30
	6.86	3.54	-0.81	0.2	400-1700	
Pt/Pt-13% Rh	6.17	5.99	-1.60	4.8	100-1700	30
	6.78	4.81	-1.07	0.2	400-1700	
Chromel/Alumel	40.15	3.83	-2.69	1.2	100-1300	30
Chromel/Constantan	59.87	40.06	-23.86	0.7	100-1000	30
Iron/Constantan	52.67	4.34	+0.74	0.8	100-800	30

Finally, the expression for the temperature distribution along the cable is determined and used to obtain $R(x)$, $G(x)$, and $V_g(x)$, by substitution of $t(x)$ for t in Eqs. (9), (11), and (12). Using these equations, the hot-zone errors can be calculated.

3. Some Analytical and Experimental Results

a. Comparison of Experimental Results

To check the validity of this hot-zone error analysis, calculations were made and checked against some experimental data that was reported in reference 4. Two different cases of "hot zone" error were calculated.

Fig. II.3. Case (1) Temperature Distributions

Case (1)--The hot junction of the thermocouple was kept at room temperature, i.e., $\approx 25^\circ\text{C}$, and varying lengths of the cable were heated to a temperature of 1593°C . The temperature distributions for this case are shown in Fig. II.3. If $R(x)$, $G(x)$, and $V_g(x)$ are treated as constants, and they can be in this case, a special form of Eq. (3) results. The source resistance for this case must also be determined from the length of cable that is at room temperature. This length is measured from the hot junction to the hot zone.

The solution of Eq. (3) gives for the emf at the cable end

$$V_\ell = \frac{V_t - V_g}{\left[(R_s \sinh L \sqrt{R/G}) / (\sqrt{RG}) \right] + \cosh L \sqrt{R/G}} + V_g, \quad (13)$$

where

V_ℓ is the emf measured at the cable end;

V_t is the emf generated by the thermocouple hot junction;

V_g is the emf generated by the thermocouple wire in the hot zone;

L is the immersion length;

R_s is the source resistance of the thermocouple;

R is the resistance per unit length of thermocouple wire;

G is the insulation resistance of a unit length of cable.

The coaxial thermocouple cable considered had the following characteristics:

Sheath Material: Pt-10% Rh;

Central Conductor: Pt;

Insulation: MgO;

Outside Diameter of Sheath: $D_3 = 0.1194$ cm;

Inside Diameter of Sheath: $D_2 = 0.08382$ cm;

Diameter of Center Wire: $D_1 = 0.03200$ cm.

The following constants were calculated for the coaxial cable and test conditions:

$$V_t = 0.143 \text{ mV at } 25^\circ\text{C};$$

$$V_g = 16.633 \text{ mV at } 1593^\circ\text{C};$$

$$R_s = 0.475 \text{ ohm for } 33 \text{ cm at } 25^\circ\text{C};$$

$$R = R_{\text{Pt}} + R_{\text{Pt-10\% Rh}} = 0.0795 + 0.0012 = 0.0807 \text{ ohm/cm at } 1593^\circ\text{C};$$

$$G = 7.65 \times 10^2 \text{ ohm-cm at } 1593^\circ\text{C with } \rho_i = 5 \times 10^3 \text{ ohm-cm.}$$

TABLE 4. Measured and Calculated Hot-zone Errors for Case (1)

Length of Thermocouple at 1593°C , cm	Hot-zone Errors, $^\circ\text{C}$	
	Measured	Calculated
38	140	201
50	242	296
145	1120	1025

The errors obtained from the calculations are compared in Table 4 with the errors measured for the different lengths considered.

Case (2)--A length of coaxial thermocouple cable approximately 112 cm long was immersed in a furnace with a temperature profile as shown typically in Fig. II.4. The maximum tempera-

ture of this hot zone was increased in steps up to 1593°C . The equation used to approximate this distribution was

$$t(x) = a \exp\left(-\frac{(x - 56)^2}{b}\right), \quad (14)$$

where a is the maximum temperature and b is an empirical constant.

Figure II.4 also shows the difference between the actual and approximated temperature distributions. As hot-zone errors are not significant below $\approx 1000^\circ\text{C}$, the best fit was made at temperatures above this value.

Fig. II.4. Case (2) Temperature Distributions

For platinum/platinum-10% rhodium thermocouple wire, Eq. (9a) becomes

$$R(t) = \frac{4[1.07 \times 10^{-5} + 4.28 \times 10^{-8}t - 6.32 \times 10^{-12}t^2]}{\pi(0.0320)^2} + \frac{4[2.14 \times 10^{-5} + 3.58 \times 10^{-8}t - 3.72 \times 10^{-12}t^2]}{\pi[(0.1194)^2 - (0.08382)^2]} \text{ ohm/cm.} \quad (15)$$

For magnesia insulation, Eq. (11a) becomes

$$G(t) = \frac{1}{2\pi} (9.0 \times 10^5 e^{-3.24 \times 10^{-3}t} + 6.0 \times 10^{15} e^{-2.07 \times 10^{-2}t}) \ln \left[\frac{(0.08382)}{(0.0320)} \right] \text{ ohm-cm.} \quad (16)$$

The constants in these equations were determined from the experimental data given in the reference. For Pt/Pt-10% Rh thermocouple wire, Eq. (12) becomes

$$V_g(t) = t(6.25 \times 10^{-6} + 4.84 \times 10^{-9}t - 1.42 \times 10^{-12}t^2) \text{ V.} \quad (17)$$

The hot-zone errors were calculated with the computer for the different temperature profiles as listed in Table 5. Each has an increasing maximum temperature.

TABLE 5. Measured and Calculated Hot-zone Errors for Case (2)

Profile No.	a, °C	b, cm	Hot-zone Errors, °C	
			Measured	Calculated
12	1593	35	138.0	144.6
11	1538	35	70.5	110.9
10	1482	35	36.8	81.3
9	1427	35	31.6	55.0
8	1371	34	26.0	34.0
7	1316	33	18.4	17.5
6	1260	32	10.5	7.3
5	1204	32	-2.2	2.6
4	1149	32	0	0.9
3	1093	32	0	0.3

b. Comparison of Analyses

Another theoretical method has been developed for calculating hot-zone errors.³¹ In this analysis the thermocouple is divided into incremental lumped-parameter networks as shown in Fig. II.5. The loop equations were solved simultaneously by a digital computer. The voltage drop arising from the current flowing in the network was subtracted from the total Peltier emf generated in the outer loop to obtain the hot-zone error.

Fig. II.5. Equivalent Lumped-parameter Circuit of a Thermocouple

The results from the two different hot-zone analyses were compared by using the sample test case reported in reference 31. The temperature distributions are shown in Fig. II.6. The data given in this report were converted to yield equations of the form given by Eqs. (9b), (11b), and (12) and the hot-zone errors were calculated. Table 6 shows the comparison of the results.

TABLE 6: Calculated Hot-zone Errors by Two Different Methods with the Same Data

Profile No.	Hot-zone Error, °C	
	ANL	Reference 31
1	-152.3	-190
2	-2.9	-6
3	-1.1	0

Fig. II.6. Temperature Distributions for Test Case

c. Prototype FARET Thermocouple Calculations and Measurements

The prototype FARET thermocouple would have had a tantalum sheath, thoria insulation, and W-3% Re/W-25% Re wires.

The dimensions of the thermocouple are:

Inside diameter of sheath: $D_1 = 0.10668$ cm;

Outside diameter of wires: $D_1 = 0.0254$ cm;

Spacing between the wires: $S = 0.0508$ cm.

For W-3% Re/W-25% Re wire, Eq. (9b) becomes,

$$R(t) = \frac{4(3.74 \times 10^{-5} + 5.01 \times 10^{-8}t + 4.19 \times 10^{-12}t^2)}{\pi(0.0254)^2} \text{ ohm/cm.} \quad (18)$$

For thoria insulation, Eq. (11b) becomes,

$$G(t) = \frac{(1.0 \times 10^6 e^{-3.00 \times 10^{-3}t} + 7.0 \times 10^9 e^{-1.15 \times 10^{-2}t})}{\pi} \ln \left\{ \frac{2(0.0508)[(0.10668)^2 - (0.0508)^2]}{(0.0254)[(0.10668)^2 + (0.0508)^2]} \right\} \text{ ohm-cm.} \quad (19)$$

For W-3% Re/W-25% Re thermocouple wire Eq. (12) becomes,

$$v_g(t) = t(1.46 \times 10^{-5} + 5.41 \times 10^{-9}t - 1.85 \times 10^{-12}t^2) \text{ V.} \quad (20)$$

The axial temperature distribution at the centerline of a tight-fit FARET fuel pin was taken as

$$t(x) = T_{in} + \frac{\Delta T}{\ell} x + (T_{max} - T_{av}) \sin \left\{ \pi \left[k + \left(\frac{1 - 2k}{\ell} \right) x \right] \right\}, \quad (21)$$

where

T_{in} is the coolant inlet temperature;

ΔT is the coolant temperature rise;

T_{av} is the average coolant temperature;

T_{max} is the max fuel temperature;

ℓ is the fuel-pin length;

k is a constant dependent on neutron flux;

x is the distance from the hot junction to the cold end.

The following conditions were selected as typical:

$$T_{in} = 250^\circ\text{C}; \quad \Delta T = 100^\circ\text{C}; \quad T_{av} = 300^\circ\text{C};$$

$$\ell = 90 \text{ cm}; \quad k = 0.14.$$

The hot-zone errors were calculated for several different values of T_{max} and for various immersion lengths (L) of the thermocouple into the fuel pin. These errors are listed in Table 7. The temperature at the thermocouple hot junction (t_a) was calculated from Eq. (21) and compared to the temperature that would be measured by the thermocouple, t_m .

TABLE 7. Hot-zone Errors* for
Tight-fit FARET Fuel Pins

$T_{\max}$, °C	L, cm	Error, °C	t_a , °C
2760	90	+1058.0	1297.4
	70	+155.8	2262.4
	50	-273.6	2735.0
	30	-124.8	2603.9
	10	-1.7	1907.0
2300	90	+675.9	1101.6
	70	+121.2	1890.3
	50	-84.8	2278.7
	30	-29.2	2176.2
	10	-0.5	1613.7
2000	90	+376.8	973.8
	70	+71.2	1647.5
	50	-33.4	1981.0
	30	-10.8	1897.3
	10	-0.2	1422.5
1700	90	+163.9	846.1
	70	+24.4	1404.8
	50	-11.1	1683.4
	30	-3.5	1618.4
	10	-0.1	1231.3
1400	90	+53.7	718.4
	70	+8.0	1162.1
	50	-2.6	1385.8
	30	-0.8	1339.4
	10	-0.0	1040.1

* $t_m - t_a$ = hot-zone error.

The temperature distribution along the thermocouple was as shown in Fig. II.8 and presented mathematically in Eq. (22). The measured hot-zone errors are listed in Table 8 for four different resistivities of the thoria insulation.

In order to calculate the anticipated hot-zone errors for the above thermocouples, the physical properties of the thermocouple materials and the furnace temperature profile must be defined. The previous equations (18, 19, and 20) used in the calculations represent the best material-property values found in the literature at the time these calculations were made. By varying the constants k_4 , k_5 , k_6 , and k_7 in Eq. (10) several interpretations of the existing thoria resistivity data can be made.

The actual axial temperature distribution with $T_{\max}$ set to 2760°C is shown in Fig. II.7 along with the distribution that would have been measured by the thermocouple system.

Fig. II.7. Temperature Distribution at
FARET Fuel-pin Centerline

Hot-zone errors have also been measured in the high-temperature furnace using typical FARET prototype thermocouples. The thermocouple construction is as follows: Sheath--0.062-in. OD with a 0.01-in.-thick wall, 20 in. long made of tantalum; Insulation--99.8% crushable thoria; Wires--0.01-in. diameter, W-3% Re/W-25% Re, spaced on 0.02-in. centers.

Fig. II.8. Furnace Temperature Distributions (Typical)

TABLE 8. Furnace Hot-zone Errors for Prototype Thermocouples

Max Temp, °C	Measured Error, °C	Calculated Error, °C			
		A	B	C	D
1600	4	1.0	16.0	2.0	8.0
1700	16	1.5	32.0	7.0	20.0
1800	33	2.0	53.0	20.0	38.0
1900	59	4.0	76.0	42.0	61.0
2000	91	6.0	99.0	69.0	85.0
2100	122	7.0	122.0	98.0	110.0
2200	153	10.0	145.0	126.0	144.0
2300	184	14.0	169.0	154.0	159.0
2400	216	19.0	197.0	190.0	189.0

The furnace temperature profile was expressed by an equation of the form

$$t(x) = a_0 + a_1x + a_2x^2 + a_3x^3 + a_4x^4 + a_5x^5 + a_6x^6 \quad (22)$$

where

$t(x)$ is the temperature along the thermocouple length, °C;

$$a_0 = +0.2578 + 0.9998t_{\max};$$

$$a_1 = -157.8 + 0.1375t_{\max};$$

$$a_2 = 316.3 - 0.2803t_{\max};$$

$$a_3 = -228.3 + 0.2024t_{\max};$$

$$a_4 = 73.47 - 0.0660t_{\max};$$

$$a_5 = -10.87 + 0.0099t_{\max};$$

$$a_6 = 0.5932 - 0.0006t_{\max};$$

$t_{\max}$ = the maximum furnace temperature, °C;

x = distance from hot junction to cold end, cm.

The results of the calculations, using four different representations of the thoria-insulation resistivity, are presented in Table 8 along with the measured values. The constants used in the resistivity equations are listed in Table 9.

TABLE 9. Resistivity Constants

Result	Constants			
	$k_4, \Omega\text{-cm}$	$k_5, \text{deg}^{-1} \times 10^{-3}$	$k_6, \Omega\text{-cm}$	$k_7, \text{deg}^{-1} \times 10^{-3}$
A	7×10^9	-11.5	1×10^6	-3.00
B	7×10^9	-11.5	1×10^6	-5.76
C	1×10^{11}	-11.5	0	0
D	7×10^9	-11.5	1×10^8	-8.05

For all cases except "A," the measured and calculated hot-zone errors agree favorably. The effect of the uncertainty in the thoria resistivity can best be evaluated by the variations in these results. The behavior of the measured and calculated hot-zone errors above 2400°C remains to be determined.

d. Conclusions

The close correspondence between the calculated and measured hot-zone errors reported in Tables 4, 5, and 8, and the excellent agreement with another type of analysis, give a good degree of confidence in the results of this analysis. It must be pointed out, however, that a large uncertainty exists in the values for the resistivity of the insulator materials.

For instance, the resistivity of thoria and magnesia as reported in the literature varies by at least an order of magnitude at a given temperature. Small uncertainties also exist in the values used for the resistivity of the thermocouple wire. The emf generated by the thermoelements above 2300°C has to be verified.

This hot-zone error analysis approximately predicts the actual errors, and therefore the placement of thermocouples that are used to measure fuel pin temperatures should be carefully planned. If the immersion length is long, careful interpretation of the resulting temperature profile must be made.

4. Prototype Design

As a first step in the prototype design of the fuel-pin thermocouples, a literature search was made to determine the compatibility of some of the materials that are considered potentially useful for thermocouples. The sheath metal of the thermocouple must be compatible with the fuel, the electrical insulation must be compatible with the sheath, and lastly, the thermocouple wire must be compatible with the insulation.

It has been found that both tantalum and tungsten do not react with uranium dioxide at temperatures up to 2760°C.³² The environment for the study was an argon atmosphere at the pressure ranging from 20 to 37 mm of mercury. Either material can therefore be used as a sheath for a thermocouple in UO₂. Tantalum was selected as the sheath material for the prototype design because it is easily manufactured into thermocouple assemblies, whereas tungsten and tungsten-rhenium alloys are not.

Thoria (ThO₂) is stable with tantalum up to 2795°C and with tungsten up to at least 2645°C. Beryllia (BeO) was found to react with tantalum above 2200°C (reference 33) and was therefore not seriously considered as an insulation material. Magnesia (MgO) also reacts with tantalum at even lower temperatures (2000°C) and was also rejected. This may mean that thoria can be used effectively as an electrical insulator providing its electrical conductivity is low enough.

The published values of the electrical conductivity of thoria are not in good agreement, and data could not be found for temperatures above 2000°C. The poor agreement appears to be due to experiments conducted with different purities of the ThO₂. Small amounts of CeO₂, Y₂O₃, or La₂O₃ tend to increase the conductivity appreciably. Elements such as magnesium and aluminum are also to be avoided because thoria is reducible in their presence at high temperature, causing a possible change in conductivity. The conductivity values reported in the literature appear to be low enough, however, so that thoria was selected as the prototype electrical-insulator material.

Many metal alloys have been studied for use as thermocouple materials at high temperatures.^{34,35} Of all these alloys, only three combinations have evolved as common, commercially available systems. These are tungsten/tungsten-26% rhenium (W/W-26% Re), tungsten-5% rhenium/tungsten-26% rhenium (W-5% Re/W-26% Re), and tungsten-3% rhenium/tungsten-25% rhenium (W-3% Re/W-25% Re). The tungsten-rhenium alloys should be compatible with thoria up to 2760°C. W-3% Re/W-25% Re was selected as the prototype design combination because of its superior mechanical properties and because of its higher output at extreme temperatures.³⁶ Table 10 gives some of the mechanical properties of the various alloys, and Fig. II.9 shows the emf output at various temperatures for the commercially available combinations. Thermocouple specifications are given in Appendix A.

TABLE 10. Comparison³⁶ of Thermocouple Mechanical Properties

Alloy	Elongation, %	Ultimate Strength, psi	Bend Ductility*	Microstructure
GE 218 W**	6	300,000	Coil	As drawn
GE 3D				
W-3% Re	3	309,000	Coil	As drawn
W-5% Re	3	420,000	Coil	As drawn
W-25% Re	5	458,000	Coil	As drawn
1750°C, 3 min, vacuum (1×10^{-3} mm Hg)				
W-3% Re	15	172,000	190	As drawn
W-5% Re	6	160,000	180	Partially re-crystallized
W-25% Re	16	220,000	Coil	Recrystallized
2200°C, 3 min, vacuum (1×10^{-3} mm Hg)				
W-3% Re	0	134,000	45-60	Recrystallized
W-5% Re	-	Too brittle to test	-	Recrystallized and grain growth
W-25% Re	3	172,000	90	Recrystallized and grain growth
2500°C, 3 min, vacuum (1×10^{-3} mm Hg)				
W-3% Re	-	127,500	0	Recrystallized
W-5% Re	-	Too brittle to test	-	Recrystallized and grain growth
W-25% Re	-	165,000	45	Recrystallized and grain growth

W-5% Re wire (0.016-in. diameter). All others (0.020-in. diameter).

*Wire bent around an 0.040-in. mandrel. Number represents angle of degrees bent before breaking.

**Too brittle to test after heating.

Fig. II.9. Thermal Emf Output for Various Thermocouple Combinations

5. Property Determinations

a. Temperature-Emf Relationships

The FARET fuel-pin thermocouples would have used the tungsten-rhenium alloy combinations, namely, W-3% Re/W-25% Re or W-5% Re/W-26% Re. These alloy combinations must be used if the fuel pin temperatures exceed $\sim 1200^{\circ}\text{C}$ because the conventional Chromel/Alumel combination becomes unreliable. The temperature-emf tables for both of the tungsten-rhenium alloy combination have been determined by the wire vendors up to approximately 2300°C . Even though the wire can be used for thermocouples above this temperature, suitable temperature-emf relationships must be established.

Bare-wire thermocouples (no electrical insulation other than the surrounding gas) were used to determine this relationship for the W-3% Re/W-25% Re combination. A table of temperature-emf was computed based on a least-squares fit with a third-degree polynomial to all the data over the range from 1000 to 2800°C as given in Table II. Over 97% of the data taken agree to within $\pm 1\%$ of both the manufacturer's average value up to 2300°C and the least-squares value up to 2800°C .

TABLE II. Measured Temperature-Emf Relationship for W-3% Re/W-25% Re Thermocouples

Temperature, $^{\circ}\text{C}$	Measured Emf, mV	Manufacturer's Emf, mV
1000	18.290	18.242
1100	20.298	20.232
1200	22.265	22.192
1300	24.185	24.083
1400	26.053	25.956
1500	27.864	27.780
1600	29.613	29.551
1700	31.295	31.269
1800	32.905	32.922
1900	34.438	34.504
2000	35.889	36.007
2100	37.253	37.406
2200	38.526	38.677
2300	39.701	39.777
2400	40.775	40.678
2500	41.742	-
2600	42.597	-
2700	43.335	-
2800	43.951	-

b. Thermoelectric Stability

The thermoelectric stability (the ability of a thermocouple to produce the same emf output at a given temperature independent of thermal history) of the tungsten-rhenium alloy combinations had to be established. Only preliminary short term tests were conducted. The W-3% Re/W-25% Re alloy combination indicated excellent short-term (less than 100 hr) stability. The W-5% Re/W-26% Re was far less stable, although preaging at a temperature of about 2000°C seemed to stabilize the temperature-emf characteristic. The final relationship did not, however, match the manufacturer's standard table. Bare-wire thermocouples were again used so as to preclude any instability that would be caused by slow chemical reactions between the thermocouple wire and the refractory oxide insulators. The results of these tests agree with those reported in the literature.³⁹

c. The Resistivity of Refractory Oxide Insulators

An important aspect of developing usable thermocouples to operate at temperatures up to 2800°C is the determination of the electrical properties, specifically the resistivity, of the refractory oxides used as insulator materials. If these resistivity values can be well defined, important computations (such as hot-zone errors) can be made to determine the best type and size of thermocouple that should be used in a given temperature environment.

Thoria appears to be the only refractory oxide suitable for use as electrical insulation in sheath-type thermocouple assemblies at temperatures above 2300°C. The reasons are:

1. It has a high melting point (~3300°C).
2. It is reported to be completely compatible with refractory metals such as tantalum, tungsten, rhenium, molybdenum, and alloys of these elements which are used both as sheath and wire elements.

Beryllia is certainly a material which can be used up to about 2000°C. It is known to react with tantalum and other materials, however, somewhere around 2200°C.

The resistivity of typical refractory oxide insulator beads used in thermocouples was being determined. Both the so-called "crushable" and "vitrified" types of insulators were being considered. Differences exist in the resistivity values of these two types, principally because of different contact area between the wires and insulation. The "crushable" type of insulation produces the greatest ratio of wire-to-insulation contact area and

will probably produce the lowest resistivity. The "vitrified" type of insulator is slip fit over the wires and will produce point or line contacts and consequently higher resistivity values.

Measurements were made according to ASTM Standard Methods of Test for Electrical Resistance of Insulating Materials, ASTM Designation: D257-61. The volume resistivity for a coaxial probe is calculated from the equation

$$\rho_v = 2\pi LR_v / \ln (D_2/D_1) \text{ ohm-cm,}$$

where L is the length of the specimen in cm, R_v is the measured volume resistance in ohms, D_2 is the largest specimen diameter, and D_1 is the smallest specimen diameter. This equation is a variation from that recommended by the ASTM, but is believed to give a more accurate result.

Since the electrical properties of thoria are not well known, it was believed that the methods for measuring resistivity should be tested on a more well-defined insulating oxide, i.e., alumina. Initial attempts at determining the temperature-resistivity properties of alumina were very discouraging since the results were lacking in any reasonable sort of repeatability. Eventually, repeatable results were obtained by careful control of the time-temperature history of the alumina.

It has been found that the resistivity of alumina (and presumably of other refractory oxides) is very much a function of its time-temperature history. This seems to be the result of two separate effects. One effect is the "freezing-in" of defects by quickly cooling the alumina, and the other is an apparent stoichiometric change in the alumina when it is heated to temperatures in excess of 1800°C in the presence of the tantalum electrodes used in the resistivity experiment. The resistivity data reported here were taken with the aid of a transistor curve-tracer, and the resistivity values represent the initial slope of current-voltage traces. All data were taken in a dry helium atmosphere.

The alumina used was of 99.7% or better purity and was prefired for 3 hr at 1950°C so that all shrinkage would take place before the resistivity probe was assembled. The prefiring was accomplished while the sample of alumina was suspended from a W-25% Re wire in a dry helium atmosphere. After this firing the alumina tube was made a part of a coaxial resistivity-measuring probe that used a tantalum outer conductor and center wire. The parts of this probe were sized to give tight press fits.

To illustrate the "freezing-in" of defects the following experiment was performed. The sample was kept at 1400°C until the resistivity stabilized at 1.82×10^6 ohm-cm. It was then heated to 1900°C for

a few minutes and quickly cooled (in about 2 min) to 1400°C, at which the resistivity was now found to be only 2.27×10^5 ohm-cm and slowly drifting higher. Then the sample temperature was again heated to 1900°C and kept there for a few minutes. Upon a slow cooling (in about 20 min) from 1900 to 1400°C, the initial resistivity value (1.82×10^6 ohm-cm) was obtained at 1400°C. This process was repeated many times with the same result (as long as the sample temperature was not in excess of 1800°C for more than several minutes which causes an apparent stoichiometric change in the alumina). Thus it is apparent that quickly cooling the sample does "freeze-in" some of the lattice defects present at high temperatures and causes an abnormally low resistivity at lower temperatures. If the sample is cooled slowly, the high-temperature defects have time to "anneal" out and the normal low-temperature resistivities will be obtained.

After the above test the coaxial probe was kept at 1900°C for a total of 5 hr and 39 min; in this time the 1900°C resistivity increased from 3.64×10^2 to 9.1×10^2 ohm-cm, where all drifting stopped. During this time the alumina sample changed from white to light gray in color. It is believed that these two effects are connected. Preliminary spectrographic and microprobe analyses indicated that the darkened alumina was not contaminated with tantalum but appeared to be substoichiometric alumina. The lost oxygen has most probably been taken by the tantalum. This characteristic darkening of alumina in the presence of tantalum at elevated temperatures should be further investigated. After the long heat at 1900°C the normal resistivities (i.e., resistivities with no "frozen-in" defects) increased slightly for temperatures above 1600°C and decreased slightly at temperatures below this point.

Fig. II.10. Resistivity of Alumina

The resistivity data shown in Fig. II.10 were taken after the long heat at 1900°C and with very slow temperature changes to avoid "frozen-in" defects. These data were essentially the same as those obtained from a second

alumina sample from the same lot and with a similar thermal history. Note that the resistivity values are somewhat above a literature average. It should also be noted that the resistivity values so obtained are near the apparent "resistivity" values for helium gas, and thus the gas gaps that exist in the resistivity probes may be the cause of the discrepancy. This possibility must be investigated, and these preliminary values of alumina resistivity should not be accepted until the investigation is complete.

Preliminary testing of pieces of vitrified thoria (99.8% or better purity) has shown that its color changes from white to very dark gray when heated above 2400°C in a helium atmosphere and in the presence of tantalum or W-25% Re. A preliminary spectrographic analysis of the darkened thoria indicated that no contamination of the sample had occurred and therefore the darkening was the result of a change in stoichiometry. What effect this stoichiometric change has on the resistivity of thoria is not known at this time.

6. Extension Lead Wire

Tungsten-rhenium alloy thermocouples were the reference design sensors for the measurement of fuel-pin temperatures. These thermocouples were to be terminated at a proposed in-vessel connector which has base-metal pins. Base-metal extension lead wire was also desirable because it has superior mechanical properties and lower cost. The splice between the thermocouple wire and the pins and/or extension lead wire at the in-vessel connector was to operate at temperatures in the range between 250 and 650°C. Extension lead wire for this temperature range was not commercially available. Various base metals were, therefore, studied for this application.

The thermoelectric output of many promising metals with reference to platinum can be found in the literature³⁸ and are listed in Table 12 at various temperatures. Table 13 lists the thermoelectric output of the stainless steel/Alumel combination selected from Table 12 whose predicted

TABLE 12. Thermoelectric Output³⁸ of Some Metals at Various Temperatures
(Reference Junction at 0°C)

Temp, °C	Output, mV					
	Alumel	8-18 Stainless	80% Ni- 20% Cr	Copper	Nickel	Chromel
100	-1.29	+0.44	+1.14	+0.76	-1.48	+2.81
200	-2.17	+1.04	+2.62	+1.83	-3.10	+5.96
300	-2.89	+1.76	+4.34	+3.15	-4.59	+9.32
400	-3.64	+2.60	+6.25	+4.68	-5.45	+12.75
500	-4.43	+3.56	+8.31	+6.41	-6.16	+16.21
600	-5.28	+4.67	+10.53	+8.34	-7.04	+19.62
700	-6.18	+5.93	+12.91	+10.49	-8.10	+22.96

TABLE 13. Stainless Steel/Alumel Lead Wire Characteristics and Errors
(Reference Junction at 0°C)

Temp, °C	Output, mV					
	W-3% Re W-25% Re	8-18 Stainless Alumel	ΔE Error	% Error in T at		
				1000°C	1500°C	2000°C
100	1.15	1.73	+0.58	-	-	-
200	2.60	3.21	+0.61	-	-	-
300	4.29	4.65	+0.36	+1.8	+1.3	+1.3
400	6.13	6.24	+0.11	+0.5	+0.4	+0.4
500	8.10	7.99	-0.11	-0.5	-0.4	-0.4
600	10.09	9.95	-0.14	-0.7	-0.5	-0.5
700	12.13	12.11	-0.02	-0.1	-0.1	-0.1

output best matches the tungsten-3% rhenium/tungsten-25% rhenium thermocouple output. Also shown in this table are the absolute error in the thermoelectric output and the percentage error in the measured temperature due to the lead wire when the thermocouple hot junction is at temperatures of 1000, 1500, and 2000°C. As the maximum error appears to be about 2% at low splice and thermocouple temperatures, the stainless steel/Alumel combination was selected as the reference material for lead wire and pin. To verify these results, three sample stainless steel (308 ELC weld rod)/Alumel thermocouple assemblies were fabricated. These were calibrated in a furnace up to $\approx 650^\circ\text{C}$ with results as shown in Table 14. This experiment verified the data found in the literature and gave assurance that this lead-wire combination would be acceptable. The repeatability of the data also gave an indication of the thermoelectric stability and uniformity.

TABLE 14. Measured 308 ELC Stainless Steel/Alumel Lead Wire Characteristics
(Reference Junction at 0°C)

Temp, °C	Output, mV				
	W-3% Re	308 ELC Stainless Steel			Average
	W-25% Re	Alumel			
151	1.86	2.49	2.49	2.50	2.49
198	2.57	3.17	3.18	3.20	3.18
253	3.48	3.96	3.97	3.99	3.97
300	4.29	4.63	4.65	4.68	4.65
360	5.37	5.59	5.61	5.64	5.61
415	6.42	6.47	6.49	6.53	6.50
470	7.50	7.44	7.46	7.51	7.47
529	8.67	8.53	8.56	8.61	8.57
580	9.69	9.54	9.56	9.62	9.57
643	10.96	10.84	10.87	10.94	10.88
152	1.87	2.53	2.54	2.54	2.54
202	2.63	3.22	3.23	3.25	3.23
259	3.58	4.06	4.06	4.09	4.07
311	4.48	4.81	4.83	4.85	4.83
360	5.37	5.59	5.60	5.63	5.61
420	6.52	6.53	6.56	6.58	6.56
476	7.62	7.54	7.56	7.60	7.57
528	8.65	8.48	8.50	8.54	8.51
588	8.85	9.65	9.67	9.73	9.68
640	10.90	10.67	10.78	10.83	10.76

Both stainless steel and Alumel are standard pin materials used in commercial connectors. In order to evaluate the adequacy of this extension lead wire completely, it was necessary to operate a sample connector and thermocouple under simulated operating conditions.

A typical fuel-pin-temperature instrument system was simulated. A tungsten-3% rhenium (W-3% Re)/tungsten-25% rhenium (W-25% Re)

Fig. II.11. SST/Alumel Lead-wire Characteristics

thermocouple was attached to a high-temperature connector which had stainless steel and Alumel pins and sockets. Stainless steel/Alumel extension lead wire was attached to the connector and terminated at a reference junction. The thermocouple, connector, and hence the splice between the thermocouple wire and extension lead wire, were heated to temperatures as high as 656°C in an argon atmosphere.

The total system characteristics are compared to the data for the original extension lead wire in Fig. II.11 and the results are tabulated in Table 15. Also shown in this table are the calculated

TABLE 15. Measured Thermocouple, Connector, and Lead Wire (302 SST/Alumel) Characteristics and Errors

Temp, °C	Output, mV			% Error in $T_m^{(a)}$ for Hot Junction Temp of		
	System	W-3% Re W-25% Re	ΔE Error	1000°C	1500°C	2000°C
149	*	1.83	-	-	-	-
209	*	2.75	-	-	-	-
257	3.90	3.55	+0.35	+1.8	+1.3	+1.2
315	4.77	4.55	+0.22	+1.1	+0.8	+0.8
376	5.70	5.67	+0.03	+0.1	+0.1	+0.1
436	6.65	6.83	-0.18	-0.9	-0.7	-0.6
487	7.59	7.84	-0.25	-1.3	-0.9	-0.9
543	8.59	8.95	-0.36	-1.8	-1.4	-1.2
543	8.58	8.95	-0.37	-1.9	-1.4	-1.3
601	9.74	10.11	-0.37	-1.9	-1.4	-1.3
656	10.85	11.23	-0.38	-1.9	-1.4	-1.3
599	9.71	10.07	-0.36	-1.8	-1.4	-1.2
544	8.65	8.97	-0.32	-1.6	-1.2	-1.1
492	7.69	7.94	-0.25	-1.3	-0.9	-0.9
482	7.44	7.74	-0.30	-1.5	-1.1	-0.9
438	6.74	6.87	-0.13	-0.7	-0.5	-0.5
426	6.51	6.64	-0.13	-0.7	-0.5	-0.5
370	5.59	5.56	+0.03	+0.1	+0.1	+0.1
366	5.58	5.48	+0.10	+0.5	+0.4	+0.4
315	4.78	4.55	+0.23	+1.1	+0.9	+0.8
270	4.16	3.77	+0.39	+2.0	+1.4	+1.3
262	4.00	3.63	+0.37	+1.9	+1.4	+1.3
205	3.18	2.68	+0.50	+2.5	+1.9	+1.7
149	2.44	1.83	+0.57	+2.9	+2.1	+2.0

*Error in measurement.

(a) T_m -- Temperature measured by W-3% Re/W-25% Re thermocouple.

percentage errors in the measured temperature due to the entire system when the W-3% Re/W-25% Re thermocouple hot junction is at 1000, 1500, and 2000°C. The maximum error appears to be ~3% at very low splice and hot-junction temperatures, which verifies the original results. As can be seen in Fig. II.11, there was a slight decrease in the emf output of the system at temperatures above 400°C as compared to the original data in Table 14. This effect is attributed to the accidental use of 302, instead of 308 stainless steel extension lead wire. The 308 alloy was found to have 2% more nickel and chromium and 1% more manganese than the 302.

In order to verify this effect, the same simulated system was used in a duplicate test except that 308 stainless steel wire was used in place of the 302 alloy. Table 16 lists this data. It can readily be seen that this data compares favorably with the original.

TABLE 16. Measured Thermocouple, Connector, and Lead Wire (308 SST/Alumel) Characteristics and Errors

Temp, °C	Output, mV			% Error in $T_m^{(a)}$ for Hot Junction Temp of		
	System	W-3% Re W-25% Re	ΔE Error	1000°C	1500°C	2000°C
122	2.15	1.44	+0.71	+3.6	+2.6	+2.4
172	2.94	2.17	+0.77	+3.9	+2.9	+2.7
242	3.91	3.29	+0.62	+3.1	+2.3	+2.1
302	4.72	4.33	+0.39	+2.0	+1.5	+1.3
301	4.73	4.31	+0.42	+2.1	+1.6	+1.4
362	5.72	5.41	+0.31	+1.6	+1.2	+1.1
426	6.78	6.64	+0.14	+0.7	+0.5	+0.5
486	7.86	7.82	+0.04	+0.2	+0.2	+0.1
573	9.44	9.55	-0.11	-0.6	-0.4	-0.4
656	11.25	11.23	-0.02	-0.1	-0.1	-0.1
582	9.77	9.73	+0.04	+0.2	+0.2	+0.1
522	8.65	8.53	+0.12	+0.6	+0.4	+0.4
450	7.30	7.11	+0.19	+1.0	+0.7	+0.7
382	6.10	5.79	+0.31	+1.6	+1.2	+1.1
320	5.10	4.64	+0.46	+2.3	+1.7	+1.6
252	4.05	3.46	+0.49	+2.5	+1.8	+1.7
200	3.30	2.60	+0.70	+3.5	+2.6	+2.4
150	2.56	1.84	+0.72	+3.6	+2.7	+2.5
100	1.66	1.15	+0.51	+2.6	+1.9	+1.8
50	0.89	0.52	+0.37	+1.9	+1.4	+1.3

(a) T_m -- Temperature measured by W-3% Re/W-25% Re Thermocouple.

These data along with the original data were then used to obtain a standard stainless steel/Alumel emf-temperature table. A least-square fit using an equation of the form $E = At + Bt^2 + Ct^3$ was made to all the data. The emf values are tabulated from 0 to 650°C in Table 17 along with the corresponding W-3% Re/W-25% Re values.

TABLE 17. Comparison of 308 Stainless Steel/Alumel Lead Wire and W-3% Re/W-25% Re Thermocouple Wire

Temp, °C	Emf, mV		Temp, °C	Emf, mV	
	SST Alumel	W-3% Re W-25% Re		SST Alumel	W-3% Re W-25% Re
0	0	0	330	5.215	4.821
10	0.179	0.096	340	5.370	5.002
20	0.355	0.197	350	5.525	5.186
30	0.529	0.302	360	5.681	5.372
40	0.702	0.411	370	5.838	5.558
50	0.872	0.525	380	5.997	5.747
60	1.040	0.642	390	6.157	5.937
70	1.206	0.763	400	6.318	6.128
80	1.371	0.888	410	6.481	6.322
90	1.534	1.015	420	6.645	6.518
100	1.696	1.145	430	6.811	6.714
110	1.856	1.278	440	6.979	6.911
120	2.015	1.414	450	7.149	7.108
130	2.172	1.553	460	7.321	7.305
140	2.328	1.695	470	7.495	7.503
150	2.484	1.840	480	7.671	7.701
160	2.638	1.989	490	7.849	7.899
170	2.792	2.138	500	8.030	8.097
180	2.945	2.290	510	8.213	8.294
190	3.097	2.445	520	8.399	8.492
200	3.249	2.602	530	8.588	8.689
210	3.400	2.764	540	8.779	8.887
220	3.551	2.928	550	8.973	9.088
230	3.701	3.093	560	9.170	9.290
240	3.852	3.258	570	9.370	9.490
250	4.002	3.426	580	9.574	9.691
260	4.153	3.596	590	9.780	9.890
270	4.303	3.767	600	9.990	10.092
280	4.454	3.940	610	10.204	10.294
290	4.605	4.114	620	10.421	10.496
300	4.757	4.290	630	10.642	10.699
310	4.909	4.465	640	10.866	10.903
320	5.062	4.642	650	11.094	11.107

The stainless steel (308)/Alumel alloy combination still appears to be the best base-metal extension lead wire known for use at high temperatures with W-3% Re/W-25% Re thermocouples. Other lead-wire combinations which might better match the above-mentioned tungsten-rhenium alloy over a wider temperature range and matches for the other alloy combinations were still being sought at the time of termination of the program.

7. Fabrication of Hot Junction and Connector-pin Termination

The attachment of the reference-design tungsten-rhenium alloy thermocouple wire to base-metal pins and the making of thermocouple hot junctions have also been investigated. In the simulated fuel-pin-instrument system and test mentioned in Sect. II.6, the hot junction and the connector-pin connections were made by a capacitance-discharge welding technique. After the test, the W-3% Re/W-25% Re bare-wire thermocouple, the junctions between the thermocouple wire and connector pins, and the junctions between the extension lead wire and the connector pins were examined.

The welded hot junction remained intact, with no evidence of extreme brittleness of either thermocouple wire. The welded junctions between the thermocouple wire and the connector pins and between the extension lead wire and the connector pins also remained intact and in excellent condition. The capacitor-discharge welding technique can, therefore, be successfully applied to the making of junctions between the reference-design thermocouple wire and extension lead wire or the connector pins.

The capacitor-discharge welding technique was also useful for fabricating hot junctions with W-3% Re/W-25% Re and W-5% Re/W-26% Re thermoelement combinations. The welding process does introduce some brittleness at the hot junctions. The junctions formed of W-3% Re/W-25% Re were found to be more rugged than those formed of W-5% Re/W-26% Re.

The most experience was gained with the use of 0.010-in.-diameter wires of the W-3% Re/W-25% Re combination. With this combination reliable welds were obtained by positioning the wires at right angles and using an energy of 5 watt-seconds with a force of 4 lb. Positioning the wires perpendicular to each other seems to promote uniform welds. The welds produced in this manner were able to withstand normal handling during assembly and also thermal cycles to temperatures up to 2800°C.

8. In-pile Tests

Prototype fuel-pin thermocouples have been successfully used to measure the centerline temperature of UO₂ fuel pellets. The first two fuel capsules had centerline thermocouples consisting of the tungsten-5% rhenium/tungsten-26% rhenium wire combination, insulated by thorium

inside the fuel region and alumina outside, and covered with an 0.062-in.-OD tantalum sheath. The irradiation facility and capsules are fully described in Sect. III.C, and a summary of the tests are given in Table 18.

TABLE 18. Summary of In-pile Thermocouple Tests

In each instance, the wires inside and outside the fuel region were insulated with thoria and alumina, respectively. All couples were sheathed with tantalum (of 0.062-in. OD).

Test No.	Thermocouple	Fuel	Capsule Gas	Centerline Temp, °C	Duration, hr	Fast Flux, nvt x 10 ¹⁹	No. of Cycles
1	W-5% Re, W-26% Re	UO ₂	A	1050	810	2.9	30
2	W-5% Re, W-26% Re	UO ₂	He	750	940	3.4	35
3	W-3% Re, W-25% Re	(UO ₂ PuO ₂)	A	1150-1345	720	2.6	20
HT-1	W-3% Re, W-25% Re	UO ₂	A	2180	~2	-	2
HT-2	W-3% Re, W-25% Re	UO ₂	He	1680	~140	-	2

The first capsule was backfilled with argon. The fuel attained an average centerline temperature of 1050°C throughout the 810-operating-hour test. The thermocouple was exposed to a calculated fast integrated neutron flux of $\sim 2.9 \times 10^{19}$ nvt. Approximately 30 thermal cycles occurred during the test. Only a slight change in emf output ($\pm 20^\circ\text{C}$ equivalent) was observed. Some of this change was due to a power increase in the capsule. The thermocouple performance was completely satisfactory.

The second capsule, which was identical to the first, was backfilled with helium. An average fuel-centerline temperature of only 750°C was achieved throughout the 940-operating-hour test. The thermocouple was exposed to a calculated fast integrated neutron flux of $\sim 3.4 \times 10^{19}$ nvt. Approximately 35 thermal cycles occurred during this test, and again only a slight change in emf output ($\pm 30^\circ\text{C}$ equivalent) was observed. Again an apparent increase of power to the capsule accounted for some of these variations. This thermocouple also performed satisfactorily throughout the life of the test.

The third fuel test capsule had a centerline fuel thermocouple made of W-3% Re/W-25% Re wires insulated by thoria inside the fuel region and alumina outside the fuel region. The sheath was 0.062-in.-OD tantalum. The initial indicated centerline fuel temperature of 1150°C steadily increased throughout the test. At the termination of the test, a temperature of 1345°C was indicated. This capsule used a mixed-oxide fuel (UO₂-PuO₂) and was backfilled with argon. The thermocouple was exposed to a calculated fast integrated neutron flux of $\sim 2.6 \times 10^{19}$ nvt during the 720-hr test. Approximately 20 thermal cycles occurred during this time.

The data obtained from thermocouple test capsule HT-1 which could contain up to three thermocouples is now presented. The W-3% Re/W-25% Re thermocouple that was used to indicate the central capsule

temperature operated continuously throughout the 2-hr in-pile test. This test was to determine if the capsule design would permit a test temperature of approximately 2400°C when used in the CP-5 reactor at maximum power. The UO_2 fuel in the capsule was spaced away from the cladding by means of

Fig. II.12. Time-Temperature History for Capsule HT-1

for 30 min. It then increased rather abruptly to about 2300°C and finally increased suddenly to 2360°C (point B). This shut down the reactor.

The cause of the sudden increase in temperature has not been explained. The capsule did, however, accomplish its purpose of showing that temperatures up to $\sim 2300^{\circ}\text{C}$ can, in fact, be achieved in the CP-5 reactor with the present capsule design.

A second capsule, HT-2, identical with HT-1, was built and backfilled with helium to produce a lower centerline fuel temperature. The W-3% Re/W-25% Re thermocouple that was used to indicate the central capsule temperature operated continuously throughout the six-day test. Figure II.13 shows the time-temperature history of the capsule as indicated by the single thermocouple. The capsule temperature behaved rather normally during initial startup, reaching an equilibrium value of about 1680°C at full reactor power of about 4.4 MW. This temperature remained essentially constant for about 40 hr. At this time the reactor was shut down routinely. Approximately 2 hr later, at reactor start-up, the capsule temperature again behaved normally. After about 2 hr at maximum power, a rather abrupt drop, then a sharp rise to very high temperature, and another sharp drop in temperature occurred. After this time the indicated temperature was very low and erratic. During this time the reactor power had been unchanged. About 6 hr prior to the termination of the test, the indicated capsule temperature suddenly increased to about 1540°C and remained relatively constant for the next 6 hr, at which time the reactor was routinely shut down. The capsule was removed from the reactor and examined in a

hot cell. The hot-cell examination revealed that the fuel had grossly cracked and fallen apart; some apparent reaction had taken place. The cause for the deteriorated appearance was not explained. The literature reveals that there should not be any reaction between tantalum and UO_2 at the particular test temperature of the capsule. An alumina thermal insulator used in the capsule could have caused this effect as alumina and tantalum have been known to react at temperatures above 1600°C . Other possible causes of the deterioration were postulated to be an impure (high content of oxygen) gas backfill or a hyperstoichiometric fuel with resulting liberation of oxygen.

Fig. II.13. Time-Temperature History for Capsule HT-2

The capsule thermocouple gave useable signals during the entire six-day test. It also indicated that a lower capsule temperature could be obtained with the helium backfill. Because of the rise in temperature near the end of the test, it is believed that the thermocouple was actually monitoring a "cracked" fuel capsule behavior. Mechanical shocks in the reactor could have caused the temperature variation.

Before additional capsules would be installed in a reactor, out-of-pile tests must be conducted in an effort to determine the exact cause of the capsule behavior.

The in-pile testing program would have subjected the prototype thermocouples to almost the actual operating conditions in FARET. These conditions include simultaneous thermocouple exposure to high temperatures ($<2000^{\circ}\text{C}$), large thermal- and/or fast-neutron fluxes, and a gamma environment. This environment would have been provided for extended periods of time (~ 1 year or $>5 \times 10^{20}$ nvt).

The following program of testing was proposed. The first tests would be simple and consist of a preirradiation calibration of the thermocouples, and then an extended period of irradiation in fuel capsule, followed by a postirradiation calibration. Such a test would not include any measurement of neutron-flux spectrum or any measurement of the test temperature other than that obtained from the thermocouples under test. The neutron flux would, of course, be estimated from previous reactor measurements. This type of test, while limited in scope, would be of some value in evaluating prototype thermocouples. Gross effects like the performance of hot-junction construction, the change of insulation resistance after and during irradiation, and compatibility performance of sheath material can be evaluated. Such tests are certainly better than no tests at all, but they lack a careful control and measurement of the test environment.

A second type of the in-pile testing was therefore needed. As a part of this testing program, a postirradiation examination would include metallographic, chemical, and spectrographic analyses to determine the extent of change in the mechanical properties, chemical combination, migration, and thermoelement composition due to transmutation. The thermocouples would also receive a pre- and postirradiation calibration.

Two separate tests are required to determine completely the effects of radiation damage. One is similar to the first tests with the exception that more careful surveillance of the environment is made. This test would be made in the more severe nuclear environment of both thermal and fast neutrons. Because some of the thermocouple materials have relatively large cross sections for thermal neutrons, transmutations, if occurring, should be enhanced by the presence of the thermal component of the neutron spectrum. The fast portion of the spectrum will, of course, be present, and changes resulting from this component will also contribute to the total damage, if any.

During this type of test, the thermocouples (~ 3) would be in contact with the fuel and, for the oxides or carbides, at temperatures in excess of 2000°C . The fuel temperature would be monitored by the use of thermal capsules employing elements or alloys having very well-known melting points. These thermal capsules would be used as a postirradiation check by determining whether the temperatures indicated by the thermocouple were actually achieved. The use of such thermal capsules in this

test would not be novel, as they have been successfully used in the Rover (nuclear rocket) program and also at ANL. The thermal capsules would be placed in the fuel and/or in the region (partial void) between the fuel and the thermocouple. The test thermocouple outputs, as well as the electrical-insulation resistance, would be monitored throughout the entire test.

The neutron flux in the region of the capsule would be continuously monitored. This information would prove useful in correlating any changes in the thermocouple output with changes in either reactor power or local neutron flux. It would also be desirable to measure the flux spectrum for thermal and epithermal components by use of the cadmium-ratio technique. The measurement of the gamma flux might also prove valuable.

A second series of identical tests would be made inside a so-called thermal converter tube. The converter tube would be "black" to thermal neutrons and provide a mostly fast-neutron spectrum. These tests would more truly represent the FARET conditions and the effects of thermal neutrons could be isolated. This portion of the in-pile program would be most valuable as it is intuitively believed that the most deleterious effects to thermocouples occur from thermal-neutron reactions.

9. Reference-junction Compensation and Multiplexing

a. Introduction

Reference-junction compensation methods had been investigated for use in the FARET cell. If the cold or reference junctions can be made in-cell, only copper leads would be needed for the electrical penetrations of the cell. This would make all the penetrations available for universal use and adaptable to the changing needs of the experimental program. Multiplexing equipment located in-cell reduces the number of cell penetrations and also the number of reference junctions needed.

b. Reference-junction Compensation

The classic ice-bath method of cold-junction compensation was considered but immediately rejected because of the water and ice required in the cell.

The simplest scheme for cold-junction compensation is one that terminates all the leads or thermocouple wires in a large equitemperature box located in the cell. The temperature inside the box is measured by some means and a correction is applied to the measured temperatures. The temperature of the box is not controlled and, therefore, different corrections must be applied as the cell ambient temperature changes. This type of compensation cannot be used if analog recorders are to be used to display the

temperatures. This method is, however, simple and requires a minimum of maintenance. It would be practical only if used with a digital data-handling system that would make the necessary corrections. Otherwise the application of the correction becomes very time-consuming.

The third method considered is known as the "hot box" reference junction. This unit maintains the cold junctions at a predetermined temperature approximately 25°C above the maximum cell ambient. This method differs from the second method only in that the reference temperature is controlled. A correction must still be applied to the temperature measurements. This can be done somewhat more easily than before as special tables are available or can be made, and analog recorders can be used to display the temperatures if special ranges are supplied. The temperature of the "hot box" is increased above ambient by the use of electric heaters which are known to burn out, and therefore this type of unit presents a remote maintenance problem should a heater fail.

The fourth device investigated was a temperature-sensitive Wheatstone-bridge circuit. One resistor in the bridge is wound with a temperature-sensitive wire and the others are stable with respect to temperature. The circuit constants are chosen so that the bridge is in balance at 0°C or the ice point. As the cold-junction (cell) temperature varies and changes the resistance of the temperature-sensitive resistor, an output signal, caused by the unbalanced bridge, is produced that corresponds to the emf produced by a thermocouple referenced to the ice point at the cold-junction temperature. To obtain automatic compensation, the bridge unbalance signal is simply added (in series aiding) to the regular output of the thermocouple. The instrument does this with excellent accuracy over a wide range of ambient temperatures. The device has an accuracy of $\pm 0.3^{\circ}\text{C}$ in ambients between 16 and 32°C , $\pm 0.6^{\circ}\text{C}$ in ambients of 0 to 16°C or 32 to 50°C . A short-term test showed that the device can be used even up to 80°C .

The standard version of this device uses a mercury battery as a power source. This battery could be easily replaced by a regulated supply located outside the cell. As the only components that would be located in the cell are the resistors and these are mounted on printed-circuit cards, remote maintenance is minimized and easily performed. This method allows the use of standard temperature tables and recorders.

The performance of the three usable systems in the presence of gamma radiation should be about the same as only radiation-resistant wire need be used. The total space needed in the cell for this equipment appears to be about the same and is equivalent to about three relay racks 66 in. high. This does not imply that relay racks would have been used in-cell but only to give an idea of the required space. If the fourth method is used, this space requirement could be relaxed considerably through the use of special packaging.

c. Multiplexing

The Wheatstone-bridge method of cold-junction compensation looks very attractive even when considered alone, but more so when coupled with a multiplexer system. Each reed-relay matrix multiplexer could sample approximately 200 signal points in one second. Assuming 1400 total points must be sampled in one second, seven such units (operating in parallel) would be needed. Only one reference junction would be needed for each multiplexer and the multiplexing equipment would utilize the space normally required by many reference junctions. For each 200 pairs of signal wires without multiplexing, only 20 pairs of wires would now be needed through the cell penetrations. The commercially available multiplexers were being evaluated for in-cell use at the time of program termination.

B. Coolant Thermocouples

1. Introduction

The thermocouples that would be used to measure the coolant temperatures in FARET were required to be compatible with the 650°C sodium environment for at least 10,000 hr and in the presence of nuclear radiation. The thermocouples were to be metal sheathed and had to be mechanically strong yet flexible enough to be installed in an instrumented fuel subassembly. Based on the results of the work reported in references 39 and 40, stainless steel sheath, alumina insulation, and Chromel/Alumel thermoelements were selected.

2. Design

The design of the reference coolant thermocouple assemblies for the instrumented fuel subassembly had been completed. The individual 0.040-in.-diameter thermocouples have a 304 stainless steel sheath, alumina insulators, and Chromel/Alumel thermocouple wire. The assemblies are rigidly fixed to the outer fuel assembly "hex" can and have the ability to measure the coolant temperature at six different axial positions in each fuel assembly. The exact position of each individual thermocouple will probably be determined to a great extent by the location of the fuel-pin thermocouples. A prototype coolant thermocouple assembly is shown in Fig. II.14. This assembly has the six thermocouples located in pairs at the inlet, outlet, and midplane of the core.

3. Results

A prototype coolant thermocouple assembly mounted in a "hex" fuel element can was proof tested in an inert gas (argon) hot-zone profile as shown in Fig. II.15. The hot-zone profile was determined from 12 furnace thermocouples spaced about 13 in. apart. This profile represents a typical simulated FARET coolant temperature distribution ($\sim 100^\circ\text{C}$ ΔT at 650°C maximum). The coolant thermocouples have determined the furnace profile

well within the maximum calculated error of 4°C , based on the worst case of a 2°C error in each of the thermocouples. The thermocouple assembly has operated successfully for over 1000 hr in this environment. It has also been thermally cycled from 650 down to $\sim 150^{\circ}\text{C}$ and back to 650°C again thirty-five times. The assembly was still operating successfully when the test was terminated.

The insulation resistance of the thermocouple assembly at various temperatures is shown in Fig. II.16.

Fig. II.14. Coolant Thermocouple Assembly

Fig. II.15. Hot-zone Profile for Coolant Thermocouple Assembly

Fig. II.16. Insulation Resistance of Coolant Thermocouple Assembly

C. Sodium In-core Flowmeters

1. Introduction

Because it was believed to be very difficult to calculate the leakage and bypass flow in the FARET vessel, it was felt necessary to measure directly the flow rate through some of the fuel assemblies. The three types of flow devices that were being investigated for this application were the turbine, magnetic, and "thermal" flowmeters. The FARET design of each device is shown in Fig. II.17.

Fig. II.17. In-core Flowmeters

2. Turbine Flowmeter

The turbine flowmeter has been used to measure liquid-metal flow rate in out-of-pile loops operating at temperatures up to 800°C.⁴¹ Several problems have resulted from this high-temperature, liquid-metal

operation. The selection of suitable bearings appears to be the biggest problem, closely followed by the selection of the magnetic material used for signal generation.

The turbine flowmeter was designed to be completely contained within a FARET fuel assembly. The meter is installed between the inlet nose piece and bottom reflector section. This limited the dimensions to the 2.33-in. hex can size.

A typical turbine-type flowmeter consists of the body, a turbine with a small four-pole magnet cast into it, and a coil mounted on the body adjacent to the turbine. When the liquid flows through the meter body, the turbine rotates at a speed determined by the speed of the fluid passing the rotor blade and the blade angle. As the magnets rotate, an a.c. voltage is induced in the coil. The frequency of this voltage is equal to twice the speed of the turbine. This a.c. voltage can be converted to a direct current proportional to input frequency and hence speed.

The body and all other parts exposed to the sodium with the exception of the bearings are to be constructed of 304 stainless steel. The guide bearing journals will be made of molybdenum and the turbine shafts of Hastelloy C. These materials were selected on the basis of their performance in high-temperature sodium.⁴² Alnico VB magnets were selected because they retain approximately 80% of their magnetization at 650°C (reference 43) and exhibit excellent stability at high temperatures⁴⁴

and in nuclear radiation.⁴⁵ A special miniature high-temperature coil had been designed. The coil assembly was to be only 0.25 in. high by 0.5 in. in diameter, as shown in Fig. II.18.

Fig. II.18. Turbine Flowmeter Coil

A turbine flowmeter had been modified for sodium service. The existing bearings and shafts were changed to the above materials. The coil was being fabricated at project termination.

3. Magnetic (EM) Flowmeter

The EM flowmeter was also designed to be completely contained within the FARET fuel assembly. Since the external dimensions are identical with those of the turbine-type flowmeter, the two are interchangeable; either can be used to measure the coolant flow rate without the need for fuel subassembly redesign.

The EM flowmeter consists of the body, magnets, pole pieces, and electrodes. The body is made of 304 stainless steel and the magnets of Alnico VB alloy. The pole pieces were tentatively selected as soft iron,

and the electrodes were stainless steel wire to reduce extraneous emfs which can be generated by dissimilar metals. For the configuration shown, a magnetic flux of about 42 G was calculated for the air gap. With this flux an output voltage of about 0.06 mV/ft/sec was expected. A prototype flowmeter had been fabricated and would have been tested in a sodium loop. Other configurations were being investigated to improve the meter sensitivity.

The magnets for the magnetic flowmeter have been fabricated and tested. The magnetic flux before temperature aging was measured and agreed very well with the calculated value of about 5000 G. The measured flux in the air gap as shown in Fig. II.19, however, was about 10 times higher than originally calculated. The high flux is attributed to the use of a fringe factor much too high in the original calculation. The higher air-gap flux in the meter increased the meter sensitivity considerably and was an unexpected advantage. The meter sensitivity is now expected to be about 0.5 mV/ft/sec.

Fig. II.19. Flux Distribution in Magnetic Flowmeter

After temperature aging the magnets at 650°C, a permanent reduction of about 20% in the magnetic flux was noted. Further aging up to about 700°C was planned.

4. Thermal Flowmeter

A so-called "thermal" flowmeter had been designed. A small amount of sodium is passed through a cylindrical hole in the center of the meter and the sodium temperature is increased by the power supplied to the heater element. Two thermocouples are used to measure the temperature rise. At a constant heater power, the temperature rise is a function of the sodium flow rate. The flowmeter was manufactured by an outside vendor.

The present design calls for a heater power of about 150 watt, with Chromel/Alumel thermocouples used to measure the temperature rise. A layer of alumina thermal insulation is placed around the heater element to decrease the heat loss to the surrounding sodium.

The exact position of the sensor in the flow stream and the dimensional variations during manufacture will influence the flow-temperature characteristic. An initial calibration was to be performed in a water loop to determine whether the flowmeter sensitivity would be sufficient for use. If acceptable, the flowmeter would have received a final performance test and calibration in a sodium system.

D. Electrical Cables and Connectors

1. Introduction

One proposed scheme for extracting a large number of in-core sensor signals from the FARET core requires an electrical connector located at the top of an instrumented fuel assembly. The connector must be capable of withstanding the high-temperature (650°C) and nuclear-radiation environment above the core and must also be sealed from the sodium or sodium-vapor environment in order to prevent short circuits. Electrical connectors and mechanical seals were being extensively tested for this application. Prototype lead-wire assemblies were designed and would have been tested after the final instrument requirements were defined.

2. Electrical Connectors

The performance of high-temperature connectors was being evaluated. A Physical Science Corporation Model PS-06-10-6 stainless steel connector using Durock D-133 insulator beads was tested at various temperatures to determine the insulation resistance. Figure II.20 shows the test connector assembly, and Fig. II.21 gives the insulation resistance between the pins and body of the connector. The values found are very adequate for most low-impedance instruments, such as thermocouples and flowmeters. The insulation resistance would be too low, however, for instruments such as ion chambers where low leakage current is a requirement. Durock #128 and #199 appear to be somewhat more suitable as their resistivity is approximately a decade better at any given temperature than the D-133.

Fig. II.20. Connector Assembly

Fig. II.21. Insulation Resistance of Connector

The contact resistance between pins did not change throughout the test. After the test the connector halves were easily separated, and a gross examination of all components showed no deterioration due to temperature.

The Physical Science Corporation Model TI-OW-22-36P-F1 weld mount receptacle and TI-06-22-36S-F1 plug with ceramic corona shield was selected as the FARET prototype design. This connector could accommodate 18 pairs of wires from an instrumented subassembly. Durock #128 was selected as the insulator beads. The connectors were purchased and testing was just starting at project termination.

3. Cable

A flexible electrical cable suitable for use with the FARET in-core instruments was available. This cable has, and retains, excellent electrical and mechanical properties when subjected to temperatures up to 680°C. The cable is commercially available from the Boston Insulated Wire and Cable Co. (B. I. W.).

a. Description

The insulating material on each wire is purified fibrous mica covered with a layer of purified braided mica. These materials are rated at 815°C for continuous use. Tracer material with inorganic pigments is used to color code the individual wires. This material exhibits excellent color fastness at temperatures up to 540°C. Wire materials selected for this particular cable are Chromel, Alumel, and stainless steel (#304). The overall cover is braided mica protected by an optional Inconel or stainless steel braid.

Fig. II.22. Insulation Resistance of Cable

The cable can then be inserted into a leak-tight stainless steel flexible armor for complete protection against the sodium vapor-argon atmosphere.

b. Test Results

A sample of B. I. W. Satellite Style IV, insulated 28 gauge solid Alumel wire in the form of a twisted pair has been subjected to temperatures as high as 680°C in air. The insulation resistance was measured at various temperatures and is shown in Fig. II.22. These values are more than suitable for this application. Gross

examination of the twisted pair before and after the heating cycle revealed that the color stripe identifying the wire type had completely disappeared. This loss of color occurs at about 540°C and is not detrimental to the performance of the cable. Otherwise, the cable remained very flexible and retained good abrasion resistance.

Similar wire has been subjected to nuclear radiation environments.⁴⁶ Fast ($E > 2.9$ MeV) neutron fluxes of 1×10^{12} nvt and gamma dose rates of 5×10^7 R/hr were obtained in the Western New York Nuclear Research Center reactor. The Satellite Style wire was subjected to the above dose rates for approximately 6 hr. This results in a total dose of 6×10^{12} nvt and 3×10^8 R. The temperature of the wire was held at approximately 150°C during irradiation. Postirradiation examination showed that the wire was in excellent condition with no change in brittleness or discoloration. The insulation resistance was found to remain unaffected by the irradiation.

A sample of a 32-conductor prototype cable had been ordered so that further tests could be made. It now appears that this electrical cable will meet all the specifications listed in Appendix B and should satisfy all the FARET requirements for high-temperature, nuclear-radiation-resistant cable.

III. EXPERIMENTAL FACILITIES

Three different types of major experimental facilities were required to carry out the FARET development program for in-core instruments. A high-temperature furnace facility was needed to develop and test fuel-pin thermocouple materials and assemblies at temperatures up to 2800°C, and a moderate-temperature furnace facility was designed and assembled to test lead wire, cable, connector assemblies, coolant thermocouple assemblies, and even full-size instrumented fuel elements at temperatures up to 650°C. The CP-5 irradiation facility was developed initially to test slip-fit-type fuel elements but was later used to test fuel-pin thermocouples under simulated temperature-nuclear radiation environments.

A. High-temperature Furnace Facility

1. Introduction

The high-temperature furnace, R. D. Brew Model 300-M, Serial 320, is a commercially available furnace (see Fig. III.1) capable of

112-6539-A

Fig. III.1. High-temperature Furnace Facility

producing temperatures up to 2800°C in a vacuum or in a variety of inert atmospheres. The furnace has a vertically oriented heating element of 2-in. diameter and 12 in. long (see Fig. III.2).

2. Temperature Range and Control

The furnace was designed to operate over a temperature range from 800 to 2800°C, with the operating temperature controlled automatically from either a power or a temperature signal. The power to the heating element is measured by means of a thermal converter, and the temperature of the hot zone is measured with an optical pyrometer permanently mounted on the furnace facility. Both variables are continuously recorded by a two-pen stripchart instrument. The stripchart recorder and an associated controller are used to control the power to the heater through a variable autoformer and a low-voltage transformer. A portable optical pyrometer is used as a standard for determining the actual hot-zone temperature at the center of the heaters. Some measured temperature profiles are shown in Fig. III.3. These data were taken with a bare-wire thermocouple while the furnace was filled with helium gas at a pressure of 27 in. of water.

It is possible to operate this furnace at temperatures less than 700°C by measuring the operating temperature with a thermocouple and using the thermocouple output to control the temperature. When this is done, the optical pyrometer normally used for control is disconnected. The furnace has been successfully operated in this manner.

3. Vacuum and Gas System

The furnace facility is equipped with a vacuum system, consisting of a mechanical pump and a diffusion pump, and a gas-handling and -analysis system.

The vacuum system is capable of maintaining pressures of 5×10^{-6} mm Hg at the lower temperatures and 1×10^{-5} mm Hg at 2800°C. In addition to providing a vacuum environment for experiments, the vacuum system is also used as a part of the inert gas-filling procedure.

The furnace may be filled to ~1 psig with inert gases such as helium or argon-5% helium. Hydrogen may be used only with proper safety precautions and approval. The major components of the gas-analysis system are oxygen- and water-content analyzers for testing gas bottles and a residual-gas analyzer for monitoring the furnace-chamber atmosphere while under vacuum operation.

1. ALUMINUM LID	5. TUNGSTEN MESH HEATING ELEMENT
2. TEST ASSEMBLY PORTS (5)	6. WATER COOLED ELECTRODE
3. WATER COOLED ALUMINUM JACKET	7. WATER COOLED COPPER JACKET
4. TUNGSTEN HEAT SHIELDS	8. SIGHT PORT

Fig. III.2. High-temperature Furnace Chamber

Fig. III.3. Hot-zone Profiles in the High-temperature Furnace

4. Furnace Construction

Tungsten is the only material used in the hot-zone region of the furnace. The heating element is made of a tungsten wire mesh and is surrounded by axial and radial heat shields that are made from tungsten sheet (see Fig. III.2). The three sections of the resistance heater are a.c. powered and are connected in an ungrounded wye configuration. The heat shields are contained by a water-cooled copper jacket that is situated within the water-cooled aluminum container that forms the outside of the furnace. Two sight ports are provided that enable visual observation of the center of the hot zone. One sight port is used for the control-system optical pyrometer and the other is available to the experimenter for reference measurements.

Test assemblies are inserted vertically through the aluminum lid and pass through the upper axial heat shields and their supporting copper plug. The test assemblies are usually supported and sealed with Conax-type seals inserted in the furnace lid.

B. Moderate-temperature Furnace Facility

The moderate-temperature furnace facility was designed to test full-size instrumented fuel elements and lead-wire connector assemblies in an inert gas environment at temperatures up to 650°C. In addition, it was decided to provide a simulated instrument penetration of a reactor vessel with its accompanying temperature gradient as well as a variable temperature profile along the furnace length. With these criteria as a basis for design, the furnace facility shown in Fig. III.4 was assembled.

The furnace body is constructed of 304 stainless steel, 5-in. schedule 40 pipe with standard flanges on both ends. It is 15 ft long from flange to flange with a 10-ft hot zone. A sectional view is shown in Fig. III.5. The heaters are 1000°C, semicylindrical, 1900-W electric heating elements, 12 in. long, except at each end where 6-in., 1000-W units are used. The power to each heated section (two semicylindrical heaters) is individually adjustable by a manually operated powerstat. By adjusting the power input to each section, almost any hot-zone profile can be established within the furnace. The hot-zone profile is measured by permanently mounted Chromel/Alumel thermocouples placed at 13-in. intervals along the hot zone and at 3-in. intervals on the simulated vessel penetration. Figure III.6 shows the temperature gradient found along the penetration when the furnace was operated at the maximum design temperature of 650°C with argon gas.

A single-point on-off controller maintains an unchanging temperature profile during a test run. The controlled temperature can be selected to be anywhere along the furnace hot zone. A 24-point stripchart instrument records the permanently mounted furnace thermocouples as well as any test-assembly thermocouples.

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Fig. III.4. Moderate-temperature Furnace Facility

Fig. III.5. Moderate-temperature Furnace

Fig. III.6. Penetration Temperature Gradient

determine the temperature drop through the fuel, and the influence of irradiation or other effects on the thermal conductivity of the fuel. The enrichment of plutonium or U^{235} in the pellet was such that a heat flux of $\sim 300 \text{ W/cm}$ was obtained, which corresponds to the heat flux that was to be expected in the test zone of the FARET core. The basic elements of the facility were still in operation at project termination, but the emphasis was upon the development of in-core thermocouples.

The loop consisted of a pressure tube immersed in the D_2O of the CP-5 reactor. Inside the pressure tube is a heat flow transducer and a fuel capsule, as shown in Fig. III.7. The heat flow transducer measures the power output from the fuel and consists of five thermocouples divided into two pairs and a single thermocouple. One pair was located at the bottom plane of the fuel and the second pair 2 in. below this. A single thermocouple was placed 4 in. below the bottom of the fuel. The thermocouples are attached to one of three equally spaced radial fins, which locate the fuel capsule centrally within the pressure tube. The pressure tube is filled with D_2O to a height corresponding to the reactor water level.

The heat flow transducer was calibrated by inserting an electrical heater into the pressure tube in place of the fuel capsule. With the reactor at full power, the power input to the heating element was held constant and the differential voltage output between selected pairs of the heat flow transducer thermocouples was integrated over a fixed time interval. The integrated voltage output as a function of power generated by the heater was obtained by this means. With the reactor at power, gamma-heating effects were taken into account by the calibration. This calibration was later used to determine power generation in the capsule.

An on-off controller maintains the furnace pressure at $\sim 2 \text{ psig}$. A vacuum pump is used to evacuate the furnace body prior to backfilling with an inert gas. At least three backfill cycles are completed prior to a heat cycle to ensure sufficiently pure inert furnace gas for all tests. A leak detector is available to determine leak rates of test components while at heat.

C. CP-5 Irradiation Facility

An irradiation facility has been installed in the CP-5 reactor for the purpose of testing sample fuel elements and in-core instruments. The facility was activated in November 1964. The initial experiments were to test slip-fit-type fuel elements.

These experiments were designed to

Fig. III.7. Fuel Test Thimble

The initial fuel capsule had a capacity for twelve fuel pellets measuring $1/2$ in. in length by $1/2$ in. in diameter, as shown in Fig. III.8. A 0.070-in.-diameter hole was provided in the center of the capsule for a fuel thermocouple. The OD of the fuel is dimensioned to have a slip fit with a capsule wall. A depleted pellet of UO_2 is located at the top and bottom of the fuel stack providing a heat transfer buffer zone. The thermocouple measures the central fuel temperature at the midplane of the fuel. Thermocouples also measure the D_2O temperature and capsule wall temperature at the fuel midplane.

UO₂ was used first to gain operating experience with the facility before using PuO₂ fuels. In the first test the 3-mil gap between the fuel and capsule was filled with argon gas. A second test was made with a capsule that was identical in all respects with the first except that helium replaced the argon. The third test was conducted with PuO₂ fuel and a helium-filled capsule.

At the conclusion of these tests, the heat flow transducer was removed and a new type of capsule inserted. This capsule, shown in Fig. III.9, was used for thermocouple performance tests. This capsule design can accommodate up to three centerline fuel thermocouples terminated at the midplane of the fuel. The capsule contained 10 fuel pellets measuring 1/2 in. in length and 0.800 in. in diameter. A 0.220-in.-diameter hole was provided for the thermocouples. The fuel pellets are spaced away from the capsule wall by 0.070-in.-diameter tantalum rods. Alumina pellets, 3/4 in. in length, are located at the top and bottom of the fuel stack to provide a heat transfer buffer zone. Thermocouples affixed to the capsule also measure the D₂O and capsule wall temperature at the fuel midplane.

Two tests were conducted with this type of capsule; the first test capsule was backfilled with argon, and the second with helium. Both used UO₂ fuel. All test results for these capsules are given in Sect. II.8.

Fig. III.8. Fuel Test Capsule

Fig. III.9. Thermocouple Test Capsule

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V. APPENDICES

A. General Specifications for Metal Sheath,
Ceramic-insulated Thermocouples, Cables, and Heaters
(Modified October 14, 1964)

1. Materials

a. Sheath: Materials shall conform to ASTM specifications. The sheath tubing shall not contain internal defects greater than 3/32 in. in an axial direction or greater than 0.002 in. or 20% of the final sheath wall thickness, whichever is larger, in a radial direction. An eddy-current technique capable of resolving defects which are one-half of the above defect dimensions shall be used to certify the sheath tubing.

b. Insulation: The composition of the insulation shall conform to the chemical analysis shown in Table A.1 and as specified on the ordering document.

TABLE A.1. Chemical Analysis of Insulators

Alumina

SiO₂--1000 ppm max
Fe₂O₃--1000 ppm max
CaO--1000 ppm max
Na₂O--1000 ppm max

B-- < 20 ppm
Cd-- < 10 ppm
Al₂O₃--99.6% min

Berylia

Al--3500 ppm max
SiO₂--160 ppm max
Ca--100 ppm max
Mg--55 ppm max
Fe--25 ppm max
Na--20 ppm max
Cu--20 ppm max

Mn--10 ppm
Cr--9 ppm
Ni--7 ppm
B-- < 1 ppm
Cd-- < 1 ppm
BeO--99.6% min

Boron Nitride

Methanol Soluble Borate--2.40% max
Alkaline Earth Oxides--0.10% max
Alumina and Silica--0.20% max
Carbon--0.008% max
BN--97% min

Magnesia

SiO₂--3000 ppm max
Fe₂O₃--1000 ppm max
Al₂O₃--1000 ppm max
CaO--1000 ppm max
B--20 ppm max
BeO--5 ppm
MgO--99.4% min

TABLE A.1. (Contd.)

Thoria

Al--500 ppm max
 Si--500 ppm max
 Mg--300 ppm max
 N--50 ppm max
 C--50 ppm max
 Ti--50 ppm max
 Ca--50 ppm max
 Fe--50 ppm max

H--20 ppm
 Zr--20 ppm
 B--10 ppm
 Na--10 ppm
 La--5 ppm
 Ce--5 ppm
 Li--5 ppm
 ThO₂--99.8% min

Stabilized Zirconia

CaO--4% max
 HfO₂--2% max
 Al₂O₃--1% max
 SiO₂--0.5% max

TiO₂--0.25%
 Fe₂O₃--0.15%
 B--10 ppm
 ZrO₂--92.0% min

c. Conductors: Materials shall conform to the highest standards of quality. Thermocouple materials shall meet the I.S.A. calibration stated on the ordering document or the emf-temperature specification attached. The material shall be preaged, where applicable, to prevent initial emf drifts. Splices shall not be present in the conductors from hot junction to cold end, including any bare-wire leads extending from the sheath at the cold end or ends.

d. Welding Rod: Consumable filler-rod material used for making closure welds shall conform to the type applicable for the sheath material specified on the ordering document.

2. Thermocouple or Cable Assembly

a. Cleanliness: The conductor and sheath are to be cleaned immediately prior to assembly. The use of compounds that contain nuclear poisons or may contaminate the insulators or may become sources which produce corrosion of the sheath or wires is prohibited at any time before, during, or after assembly.

b. Insulators: The insulators must be baked at a minimum temperature of 1800°F to remove contaminants and moisture immediately prior to assembly and must be kept in a relatively dry atmosphere during assembly. The insulators must be firmly compacted during assembly to at least 90% of theoretical density.

c. Process: The sheath, insulators, and conductors are to be processed into a homogenous assembly by suitable manufacturing techniques.

d. Anneal: The finished product shall be fully annealed where applicable. Annealing shall be done in a controlled-atmosphere furnace and shall produce a finished product having a bright, clean sheath surface.

e. Electrical and Mechanical Characteristics: The characteristics of the finished product shall conform to those specified on the ordering document.

f. Open Sheath End Finish: The open ends of the sheath shall be finished square and smooth.

g. Sealing of Open Sheath Ends: To ensure that the insulation resistance is maintained in the final product, all open ends are to be sealed with a silicon varnish or waterproof cement capable of withstanding a minimum temperature of 212°F unless otherwise stated on the ordering document.

h. Thermocouple Junction: As specified on ordering document:

(1) Grounded Junction shall have a spherical welded end closure with a maximum thickness "T" equal to the sheath diameter divided by two ($OD/2$) and a minimum thickness equal to the sheath diameter divided by four ($OD/4$).

GROUNDING JUNCTION

(2) Insulated Junction shall have a spherical welded end closure identical to that described above. The distance "D" from the welded end closure to the hot junction shall be a maximum of $OD/2$ and a minimum of $OD/4$.

INSULATED JUNCTION

(3) The outside of the welded end closure shall be smooth and within the outside tolerance specified in Sect. 2.e.

i. Cold End Termination: As specified on ordering document.

j. Straightness: Standard material will be straight so that the minimum radius of any kinks in the sheath will be at least 500 times the

diameter of the sheath. When the finished thermocouple assembly is placed free on a flat surface, the sheath shall not deviate from a straight line by more than ± 2 in. When preformed thermocouple assemblies are required, this specification will hold for sections between bends.

3. Performance Tests

a. Surface Condition: The surface finish of the sheath of the final product shall not have a roughness greater than 50 microinches.

b. Surface Defects: There shall be no cracks or defects such as gouges, dents, die, or tool marks greater than 0.002 in. in depth on the surface of the sheath of the final product as evidenced by an examination at 5X.

c. Hot-junction Integrity: A length of thermocouple extending a minimum of 4 in. from the hot junction shall be radiographed in two views 90° apart and perpendicular to the thermocouple axis. The radiographs shall not show evidence of cracks, notches, crevices, voids, inclusions, or local reduction in dimensions of the wires, sheath, or welded end closure. The radiograph shall show positive evidence that a connection of wires is made at the hot junction and that the dimensions of Sect. 2.h. have been conformed to.

A copy of the radiographs shall be shipped with the thermocouples and be easily identified with the individual thermocouple.

d. Electrical Continuity: The resistance of each thermocouple or individual wire must be measured at room temperature after the below calibration has been performed, and be within 10% of the calculated resistance for the type and size of wire being used. The measured resistance value shall be reported as well as the finished wire size.

e. Insulation Resistance: Thermocouples or cables having insulated junctions must be tested for insulation resistance in accordance with Sect. 2.e. and shall conform to that specification. The measured resistance shall be reported.

f. Calibration: A one-point calibration of each thermocouple of the finished thermocouple assembly, including any connectors, shall be made at approximately 50% of the maximum reliable operating temperature of the thermocouple wire or sheath material, whichever is lower. The calibration temperature and resulting emf as referenced to a cold junction of 0°C shall be reported. The temperature calculated using N.B.S. Circular 561 shall agree with the true temperature of the measuring junction within $\pm 1^\circ\text{C}$ up to 260°C and $\pm 3/8\%$ above 260°C or as per ordering document specification.

g. Sheath Integrity: Any time a weld or braze is made to the sheath material, a sheath-integrity test shall be performed to determine the structural integrity of the outside sheath. Each weld or braze, if more than one is required for the finished product, shall be tested individually and then the final finished product tested as an assembly. The outside of the weld or braze is exposed to an ambient helium pressure of 2000 psig nominal while simultaneously maintaining a pressure of 50 microns of Hg or less on the inside. Conditions of pressure and vacuum will be maintained for a period of time no less than one hour during which time the unit will be monitored with a mass-spectrometer helium-leak detector. If a measurement of 1×10^{-8} or greater standard cc/sec helium is obtained, the unit will be rejected as having an excessive leak. For acceptable welds or brazes, the calculated leak rate of each weld or braze shall be recorded and included as a part of the test report.

h. Certification and Test Reports: Material certifications, as well as test and inspection reports covering each individual thermocouple, cable, or heater shall be supplied to the purchaser.

4. Shipping

a. Marking: Material shall be identified by a tag securely fastened to each individual thermocouple or cable. The tag shall contain sufficient information to identify the item and correlate it to certification and test reports. Each wire shall be suitably color coded to identify the polarity or type of wire. A diagram or table must accompany the material interpreting the identifications.

b. Packing: The material shall be shipped straight unless specified otherwise on purchase document and in a suitable container to assure adequate protection from damage during handling and shipment.

B. Specifications for High-temperature Cable

Environment: The cable shall be exposed to inert gases, such as argon and helium, and vacuums as low as 1 micron. The materials used for construction, including jackets, tapes, cores, etc., shall not contain materials which will produce outgassing up to the maximum temperature specified in this specification.

Temperature: The entire cable shall be rated for continuous operation at 1200°F.

Nuclear Radiation: The cable shall be subjected to total gamma doses of at least 10^{10} R.

Insulation Materials: Only inorganic materials are to be used. The boron content of any material shall be less than 5 ppm.

Insulation Resistance: Must be at least 100 megohms per foot between wires and between any wire and outer braid with 500 V d.c. applied at 1200°F.

Wire Materials: Thermocouple materials shall meet the I.S.A. calibration stated on the cable-arrangement drawing. Other materials shall conform to the highest standards of quality.

Wire Identification: The individual wire insulation shall be coded to identify the wire materials. The marking materials shall not produce outgassing up to the maximum temperature specified, but the markings themselves can be destroyed after the first thermal cycle.

Cable Arrangement: See Drawing RE-1-40844-A.

Cable Size: See Drawing RE-1-40844-A.

Cable Flexibility: The finished cable must be able to be formed to a 6-in. radius. A section of cable, bent through a 90° arc on a 6-in. radius and straightened for 25 cycles, must not change the insulation resistance or break the wire, outer braid, or outer armor. This test applies at any temperature including the maximum specified.

Outer Braid or Armor: See Drawing RE-1-40844-A.

Drawings: The vendor shall supply suitable reproducible drawings showing construction, materials, and dimensions. The wire identifications shall also be included.

- A. INORGANIC INSULATION
B. INCONEL OUTER BRAID
C. INORGANIC FILTER
D. BOSTON INSULATED WIRE COMPANY
SATELLITE STYLE IV WIRE WITH
.150/2/2, 16 CARRIERS, 34.5 PICKS
PER INCH MICA BRAD, 0.080 ± 0.005 O.D.

NOTES:
32- #28 SOLID B&S GUAGE WIRE.
CHROMEL - ALUMEL TO BE I.S.A.
TYPE-K SPECIAL LIMITS OF ERROR WIRE.

							APPROVED CONST.	DATE	CHIEF DRAFTSMAN	DATE	NEXT ASSEMBLY	NO. REQUIRED
							STAFF APPROVAL		CHECKED		ARGONNE NATIONAL LABORATORY THIS DRAWING IS THE PROPERTY OF THE ARGONNE NATIONAL LABORATORY	
							REPRESENTATIVE	GROUP	DRAWN BY		TITLE	
							TOLERANCES - UNLESS OTHERWISE NOTED FRACTIONAL ± DECIMAL ± ANGLE ± REMOVE ALL BURRS				CABLE ARRANGEMENT	
							MATERIAL				SCALE	DRWG. NO.
SYM.	ZONE	CHANGE				DATE	BY	CHK.	SEE DRWG.		N.T.S.	RE-1-40844-A

REORDER NO. HK-9-11241-A

VI. ACKNOWLEDGMENTS

The authors would like to acknowledge the excellent technical contribution made by Togan Zeren, now affiliated with the Middle East Technical University, Ankara, Turkey, to the high-temperature thermocouple program during his appointment at Argonne. The important ideas and suggestions of Thomas Bump resulted in the design of the magnetic and thermal flowmeters. We wish to particularly thank and acknowledge John Folkrod for the design and installation of the CP-5 Irradiation Facility and thermocouple test capsules and William Kann for the design of the instrumented subassembly. Our appreciation goes to Walter Simmons, Abraham Smaardyk, and Walter Lipinski for their guidance and encouragement throughout the sometimes difficult periods of program execution and report writing.

We also wish to thank and commend the following Reactor Engineering personnel: Robert Grench, who helped with the final "hot zone" error computer programming; Warden Deets for building the extension lead-wire test thermocouples and for taking the required experimental data; Ralph Esposito for building the initial high-temperature connector test loop and for conducting the required tests; and to Nicholas Peters for conducting the initial tests on the high-temperature cable and for reducing the test data.

Our special thanks and commendation to Martin Glass for his excellent contributions in many development areas. He personally redesigned and constructed the turbine flowmeter coil. His contributions to the solutions of assembly problems with the magnetic flowmeter were found to be outstanding. His many practical ideas on the fabrication of our bare wire high-temperature thermocouple assemblies and his craftsmanship on their assembly were invaluable to this program. He has also contributed greatly to the piping and electrical modification made to the High-temperature Furnace Facility.

Also, our special thanks and commendation to William Clemmons who contributed much to the high-temperature connector and cable program. He personally designed and fabricated the test stand for the Moderate Temperature Furnace Facility, assembled the furnace, and connected the control and heating circuits. He conducted an innumerable number of leak tests on sample high-temperature connectors and some test seals. He assembled preliminary lead-wire assemblies and conducted the necessary tests. His contributions to the design and tests of the coolant thermocouples were outstanding.

We do not wish to forget those in other Divisions who helped analyze our many test specimens. To Doris Huff and Virginia McCreary of the

Chemistry Division for the spectrographic and chemical analysis, we express our thanks. Norman Lapinski of the Metallurgy Division deserves our highest praise for the excellent radiographs. To Anthony Baudino and Joseph Florek of the Metallurgy Division, for their fine assistance in preparing the samples and taking the microphotographs of our specimens, we express our highest commendation. And to Phyllis (Walker) Lukehart of the Applied Mathematics Division for writing the original Kutta-Merson Program, our deepest appreciation.