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DESIGN OF A CAPSULE FOR
IRRADIATION NEAR 2000 C

by

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DESIGN OF A CAPSULE FOR IRRADIATION NEAR 2000 C

W. J. Zielenbach and J. W. Ray

A capsule was designed for irradiating samples at temperatures between 1600 and 2000 C at a heat rate of 2.8 kw per ft. A useful range of temperature control was obtained using a binary gas mixture of variable composition in the outer capsule annulus. Heat-transfer studies of various configurations were conducted to determine the best scheme for temperature measurement. In the concept chosen, a sheathed thermocouple was located in a thick section of cladding which was removed from the point of maximum temperature by about 180 C. Two experiments were conducted with additional bare, stranded thermocouples attached to the exterior of the cladding at the point of maximum temperature to verify the predictions. Measured thermal gradients correlated with the predicted values but the overall performance of the sheathed thermocouples was poor. Temperatures of 1700 to 1800 C were obtained.

INTRODUCTION

A study was undertaken to develop a capsule for a series of experiments to evaluate the performance of refractory fuels in irradiations at temperatures between 1600 and 2000 C. The only restriction on this study was that the specimen size and, in particular, the pin OD be fixed to conform with that employed in irradiations at low temperatures.

Considerations such as heat transfer, thermocouple location, uniformity of temperature, and structural integrity were emphasized in the analysis of selected concepts. The objective was to obtain a system with maximum utility and minimum compromise with respect to the following criteria:

- (1) Exposures at 1600 to 2000 C at burnup rates in the range of 2×10^{19} to 5×10^{19} fission per cm^3 per normal 3-week cycle of the Battelle Research Reactor (BRR).
- (2) Capability for accurate temperature measurement, i.e., measurement of the temperature of the specimen or of a temperature that could be extrapolated to it with confidence.
- (3) A useful range of temperature control.
- (4) Inclusion of a sufficient number of samples to yield a significant amount of data from a single capsule.

Temperature dictated many of the limitations imposed on the basic capsule configuration. Liquid-metal heat-transfer media were ruled out either because of their high vapor pressure or their unproven compatibility with refractory alloys at temperatures above 1600 C. This limitation dictated the use of a gaseous or vacuum environment surrounding the specimens, and concomitant large temperature gradients between the specimens and their enclosure at the desired heat generation rates.

MAJOR DESIGN CONSIDERATIONS

The study was intended to develop the following major items in the design of this capsule and to evaluate them in a practical experiment:

- (1) The method of monitoring temperature
- (2) The method of controlling temperature
- (3) The amount of nuclear heating required.

There is an interdependence between these items, especially the last two.

Temperatures of the specimens could not be determined accurately from thermocouples located in the gas space surrounding the specimens because of the high temperature gradient in this region and the resultant sensitivity of the temperature recorded by a thermocouple to its position. Temperatures measured at the enclosure wall could not be confidently extrapolated to obtain the temperatures of the specimens because of the large temperature differential and the associated uncertainties in heat-transfer calculations. A configuration was needed which would allow the placement of a thermocouple in a region of minimum temperature gradient and in close proximity to the fuel. Many concepts were devised; detailed heat-transfer analyses were performed on a computer to evaluate those with the greatest promise. Only the more promising concepts are discussed in detail in this report. The heat-flow analysis is described in Appendix A.

When specimens are heated at 1800 C in a gaseous medium, a large proportion of the heat transfer is radiative in nature. Since radiative heat transfer varies as the fourth power of the absolute temperature, it appeared that temperatures would be relatively insensitive to small variations in the neutron flux and emissivity of surfaces. However, if the estimated heat generation rates were significantly different from those actually realized in-pile, it could become difficult or impossible to adjust the temperature of the specimens up or down the required amount by regulating the heat-sink temperature.

A nuclear mock-up of the complete capsule was necessary to determine the effective thermal-neutron flux at the specimen. Data from this experiment were used to calculate nuclear heating rates, to fix the optimum size of the capsule annuli, and to predict operating temperatures.

Temperature Monitoring

Figure 1 depicts several of the many configurations considered. Each of them contributed to some extent to the design of the final configuration. Figure 1a shows the type of specimen which was immersed in Li₇ in irradiations at lower temperatures. At 2000 C in the absence of lithium there is no satisfactory location for a sheathed thermocouple to obtain useful temperature data. A preliminary scheme, depicted in Figure 1b called for the placement of a thermocouple in an axial hole in the cladding. Direct temperature measurements could be obtained, but the degree of restraint offered by the thick, although weak, cladding could not be assessed from the limited amount of long-term, high-temperature strength data available for refractory alloys.

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FIGURE 1. CONFIGURATIONS CONSIDERED FOR MONITORING THE TEMPERATURE OF SPECIMENS AT 2000 C

The concept of Figure 1b was modified to create the configuration shown in Figure 1c. Ideally, if dimensions were adjusted properly, the temperature of the specimen in the thin cladding and the monitored temperature would be nearly identical. However, a radiation baffle was needed around the thick section to offset the radiative heat losses from the large surface area in this region. The configuration involving the baffle was discarded because of uncertainties created by the additional radiative surfaces, and because of possible difficulties that could be introduced in the assembly of an already crowded system. A variation of this configuration was adopted for the final design and is discussed in a later section.

Another configuration, which was subsequently discarded, is illustrated in Figure 1d. The centerline thermocouple offered the advantage of more direct temperature measurement. However, heat-transfer and compatibility problems involving the thermocouple sheath and the cladding in the thermocouple well were anticipated. It was noted that the thermocouple in Figure 1d resides at temperatures above that of the cladding OD. It has since been demonstrated that compatibility problems do exist at temperatures above 1800 C in commercial tungsten-rhenium, BeO-insulated, tantalum- or niobium-sheathed thermocouples.

A bare thermocouple inserted between the ends of two specimens (Figure 1e) also afforded the possibility of obtaining data at a location not far removed from the maximum temperature since axial heat flow in the region of the thermocouple would be quite small. The use of a commercial thermocouple was postulated with the end of the sheath removed to expose the bare thermoelements. Difficulties were anticipated in maintaining the fuel at the upper end of one specimen as shown, in maintaining adequate dielectric properties of the wires in the exposure zone, and in sealing the containment shells against fission-gas seepage through the crushed insulator of the thermocouple into the capsule lead tube. A variation of this configuration was considered which had two specimens in the same cladding with an interior plug separating them. The bead of a sheathed thermocouple would have been inserted in a radial hole in this plug. However, this configuration would have required that the thermocouple be bent on a very small radius to fit in the hole.

The design which evolved from these studies is shown in Figure 2. The sheathed thermocouple was located in an axial hole in a 0.12-in.-thick (0.305 cm) region of the cladding surrounding the lower 0.25 in. (0.635 cm) of the 1-in.-long (2.54 cm) core. The remainder of the 0.21-in.-diameter (0.534 cm) core was encased in a 0.02-in.-thick (0.0508 cm) cladding. The void above the fuel was 5/16 in. long (0.794 cm) and the total length including end caps was 1-7/16 in. (3.64 cm).

Heat-transfer studies of this configuration at a typical heat generation rate indicated that a maximum temperature of 1780 C would be expected at the surface of the specimen at its midplane and that the temperature gradient to the thermocouple would be approximately 170 C. This solution was obtained using the following assumptions:

- (1) The fuel was 10 percent enriched UC (3.3×10^{21} atoms of U235 per cm^3).
- (2) The heat generation rate was 2.8 kw per ft and was uniform throughout the fuel.
- (3) The specimen was immersed in a helium environment.

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FIGURE 2. SPECIMEN DESIGN

- (4) The emissivity of the cladding was 0.2.
- (5) The heat was transferred to a 0.75-in. -ID (1.905 cm) containment wall at 550 C (emissivity = 0.4).

The heat removed from the specimen through the helium around the specimen was transferred 50 percent by conduction and 50 percent by thermal radiation.

Temperature Control

A technique involving the use of various combinations of two gases of different conductivities was selected for control of temperature. The temperature of the inner containment was regulated by varying the composition of a mixture of helium and nitrogen in an outer annulus. The gas mixture was separated from the inner containment by a annulus containing static helium and an intermediate wall. However, for this capsule the intermediate wall was not necessary, and the gas annulus was located between the inner containment and the water-contacting stainless steel shell. Heat-transfer studies indicated that the temperature of the inner containment would vary from 550 C with pure helium flowing in the annulus to 1050 C with pure nitrogen flowing in the 0.04-in. (0.1015 cm) outer annulus. This temperature variation would produce a change of 200 C in the temperature of the specimen. Because of its operating temperature and because of possible exposure to nitrogen, niobium-1 w/o zirconium was chosen as the material of construction for the inner containment. It was realized that some nitriding of the refractory alloy would occur, but by fixing its maximum allowable operating temperature at 1050 C, serious degradation of properties by nitriding would not occur.

Nuclear Mock-up

Tungsten-26 w/o rhenium, a material possessing a relatively high neutron cross section, was selected as the candidate cladding material because of its fabricability and refractory nature. Accordingly, a nuclear mock-up study was necessary to examine changes in the temperature profile caused by the variations in diameter of the cladding and by depression of the flux and heat generation in the fuel inside the thick section of cladding.

Two specimens were irradiated in the study. The cladding was simulated by 0.25-in. -OD (0.635 cm) by 0.02-in. -wall (0.0508 cm) tungsten-26 w/o rhenium tubes surrounded by hollow cylinders, 0.25 in. ID (0.635 cm) by 0.10 in. wall (0.254 cm), fitted over the bottom 5/16 in. (0.794 cm) of the length of the smaller tubes. The tubes were open at the top, to facilitate removal of the dosimeters and specimens, and closed at the bottom. The overall length was 1-3/8 in. (3.49 cm). One of the outer cylinders was a sintered compact of tungsten-rhenium, and the other was machined from molybdenum. The effect of both materials was evaluated since a probability existed that the local depression of the neutron flux by the thick section of tungsten-26 w/o rhenium would create too great a temperature gradient for accurate temperature prediction. If this proved to be true, claddings could be fabricated with a thick section of molybdenum bonded to the tungsten-rhenium.

The fuel was simulated by pellets of 10 percent enriched UC, 0.21 in. OD (0.534 cm) by 1 in. long (2.54 cm). Three bands of fully enriched uranium foil, 0.0005 in. thick (0.00127 cm), were wrapped in 1/16-in.-wide (0.159 cm) grooves around the periphery of each pellet at various locations to serve as dosimeters. An additional piece of foil was placed in a 0.04-in.-diameter (0.1014 cm) hole in the centerline of each pellet. The dimensions of the grooves and hole were designed to match the number of U^{235} atoms removed from the pellet with the number of U^{235} atoms in the fully enriched dosimeter foils. The specimens were supported in a double walled capsule which simulated the neutron cross-sectional properties of the proposed capsule. The experiment was irradiated in the BRR for 50 min at approximately 0.1 percent of full power. After a decay period of several hours, the experiment was disassembled, and the dosimeters were recovered and analyzed.

The data from the dosimeters in the nuclear mock-up indicated that the ratio of the average flux in both specimens to the unperturbed flux in the local vicinity (ϕ_e/ϕ_U) was 0.2. In the specimen surrounded by tungsten-rhenium the average flux was 40 percent lower in the thick section than in the thin section.

The heat generation rates from these neutron fluxes were used to predict the temperatures expected. Assuming a uniform heat generation rate, the heat-transfer studies predicted that the maximum temperature at the surface of the cladding would be 1740 C and that there would be a 160 C drop to the position of the thermocouple. However, when the reduced heat generation in the thermocouple region was included, the maximum temperature of the cladding was reduced to 1700 C and the drop to the thermocouple increased to 180 C. Further computation also predicted that the temperature of the specimen could be increased to 1850 C with nitrogen (no helium) flowing in the outer annulus and that the drop in temperature to the position of the thermocouple would remain unchanged.

Since the flux depression inside the heavy section of cladding did not appear to cause a significant change in the temperature profile, the entire cladding was fabricated from tungsten-26 w/o rhenium.

Resultant Design

These studies led to the capsule design shown in Figures 3 and 4. Six specimens could be located in helium in the inner shell of niobium-1 w/o zirconium. The specimens were secured and centered in a structure of thin, triangular molybdenum plates supported on three 1/16-in.-diameter (0.159 cm) molybdenum rods. These rods were attached to and hung from the base of the stainless steel capsule header by individual brazed joints. A sheathed thermocouple was lodged in the thick section of each specimen. The 1/16-in.-diameter (0.159 cm) thermocouples consisted of tungsten-5 w/o rhenium versus tungsten-26 w/o rhenium thermoelements sheathed with tantalum and insulated with crushed high-purity BeO in the hot zone; crushed Al_2O_3 served as insulation in the thermocouple outside the capsule. A brazed seal was made at the point of exit of the thermocouples through the capsule header.

The seals on the niobium-1 w/o zirconium inner containment were made by brazing the top of the shell to the capsule header and by welding an end cap in the bottom (see Figure 5). When the primary containment was completed, it was evacuated and outgassed

FIGURE 3. GENERAL CAPSULE DESIGN

a. X-Ray of Specimen Section

b. Photograph of Specimen Assembly and Capsule Header

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FIGURE 4. CAPSULE SUBASSEMBLY

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FIGURE 5. CAPSULE PARTS FOR HIGH-TEMPERATURE IRRADIATION EXPERIMENTS

at 200 C for 16 hr. The chamber was then backfilled to a pressure of 2 psia with helium which had been passed through a liquid-nitrogen cold trap. The backfill tube was heated, crushed, and welded to form a seal. A triangular spacer was attached to the bottom of the inner shell to center it within the outer shell.

A secondary system for measuring temperature was included in the design. Sheathed Chromel-Alumel thermoelements were installed in grooves on the exterior of the inner containment with their junctions opposite the midplane of the pellets. These sheathed assemblies were passed through individual holes near the periphery of the header (Figure 4).

The mixture of helium and nitrogen entered the upper end of the outer annulus and exhausted from the bottom through a small tantalum tube positioned in a groove in the outer surface of the niobium-1 w/o zirconium containment. Both the inlet and outlet tubes passed through holes at the top of the header. Stainless steel tubes 1/8 in. in OD (0.318 cm) were used between the capsule and the temperature control system*. The two gases were mixed at a tee joint several feet above the capsule header.

An end cap was welded into the bottom of the stainless steel outer shell. The inner shell and header assembly was positioned inside the outer shell with the top of the header about 1 in. below to top of the outer shell. In one operation the outer shell, the sheathed Chromel-Alumel thermocouples, and the gas tubes were brazed to the header. A 23-ft length of 1-in. -OD stainless steel tube was welded to the upper end of the capsule to isolate the gas tubes and thermocouple leads from the reactor water. Compensated lead wire was used to extend all thermocouple leads to instrument connections above the level of the BRR pool. An epoxy resin seal was formed inside the top of the stainless steel tube to contain pressurized helium. A short section of the insulation was removed from the electrical wires in the region of the epoxy resin to be certain that a reliable seal was obtained. The gas tubes were also sealed into this joint.

EXPERIMENTAL RESULTS

Confirmation Experiment

The first irradiation was designed to obtain data on the temperature profiles of the specimens for comparison with the heat-flow analysis. Since this experiment was to be operated principally for confirmation of the design, only three specimens were incorporated in the capsule. A commercially produced, tantalum-sheathed tungsten-5 w/o rhenium versus tungsten-26 w/o rhenium thermocouple was located in the thick section of each specimen. To obtain thermal gradient data, three stranded bare-wire tungsten-rhenium thermocouples were attached to the exterior of the central specimen, one at the maximum temperature location, one at the top of the fuel, and one on the outside of the thick section**. The assembly is shown in Figure 4b before the stranded elements were affixed to the specimens.

* The temperature control system is described in Appendix B.

** The stranded thermocouples are described in Appendix C.

At the start of the irradiation, the maximum temperature of the center specimen was approximately 100 C below that predicted by the heat-flow analysis. Also, the temperature difference between the bare-wire thermocouple and the thermocouple in the collar was 90 C as compared to a predicted difference of 180 C. Factors that might account for a low reading from the bare-wire thermocouple include poor thermal contact between the thermocouple and the surfaces of the cladding, and shorting of the thermoelements at a short distance from the junction. Since the maximum temperature and the thermal gradient were both low by approximately the same amount, it is possible that the maximum temperature was actually 100 C higher.

Inspection of the data from this initial experiment showed that marked degradation of the sheathed tungsten-rhenium thermocouples started after about 600 hr of irradiation. The downward trends of the outputs of the sheathed thermocouples were severe, the greatest being an indicated change of 250 C in the thermocouple on the center specimen; this thermocouple displayed the highest output at the start of the experiment (30 C higher than the other two thermocouples) and the lowest output at the conclusion of the irradiation (100 C lower than the other two). Over the course of the irradiation some downward drift of the output of the bare-wire thermocouples was also evident, but this was attributed to a reduction in neutron flux caused by burnup in the reactor.

Full-Scale Experiment

The second capsule contained six specimens in an argon environment. Argon was used in place of helium to obtain higher temperatures. Heat-flow predictions indicated that the maximum temperature would be 1900 C and that the temperature would drop 200 C to the thermocouple. It was expected that the two specimens at each end of the array would receive about 85 percent of the maximum flux based on the flux profile of the BRR.

A sheathed thermocouple was placed in the thick section of each specimen. Tungsten-rhenium thermocouples sheathed in tantalum were inserted in the lower three specimens, while elements sheathed in molybdenum-50 w/o rhenium were employed with the upper three specimens. Because of the uncertainty in the temperature difference between thermocouples located at the point of maximum surface temperature and in the collar, one bare-wire thermocouple was attached to the exterior of the fourth specimen to monitor the maximum temperature*. Figure 6 is a reproduction of a neutron radiograph of this capsule prior to irradiation.

When the irradiation of the second experiment was initiated, the reactor power was increased in steps. During this period it was noted that the thermocouple in the third specimen was inoperable. When the last power increase was made, 90 percent to full power, the outputs of all thermocouples increased normally except that of the sheathed thermocouple in Specimen 4. The output of this thermocouple shifted downward slightly and remained low for the remainder of the irradiation as if a short had occurred near the hot zone. In the absence of data from the sheathed thermocouples on the two specimens operating at the highest temperatures in the system, data obtained from the other specimens were used to plot a temperature profile for estimation of the temperatures at the location of the sheathed thermocouples in Specimens 3 and 4. At a power

* Specimens were designated 1 through 6, starting at the top.

FIGURE 6. PREIRRADIATION NEUTRON
RADIOGRAPH OF THE
SECOND CAPSULE

level of 2 Mw a temperature of 1880 C was monitored on the exterior of the cladding of the fourth specimen by the bare-wire thermocouple. Because of compatibility problems between the cladding and fuel at temperatures in excess of 1800 C, this temperature was reduced below 1800 C by changing control-rod positions. The gradient from the monitored temperature to the location of the shorted thermocouple was estimated to be 220 C. This was in agreement with the value predicted by heat-transfer analysis. There was a 200 C difference in the temperatures of the center and top specimens.

Neutron radiographs of this capsule, and of the preceding experiment, were taken between each reactor cycle to record any changes in dimensions. These indicated that more clearance than that shown in Figure 6 was needed between specimens to accommodate the differential thermal expansion of the specimens and the support assembly.

The outputs of the sheathed tungsten-rhenium thermocouples degraded somewhat during the irradiation, but not to the degree observed in the previous experiment. The output of the bare-wire thermocouple showed no degradation throughout the irradiation.

CONCLUSIONS

It has been demonstrated that it is possible to design and operate a capsule capable of containing nuclear fuels at 2000 C at heat ratings of the order of 2.8 kw per ft. Temperature control was achieved using a flowing gas in an outer annulus of the capsule. The temperature of the specimen could be varied about 200 C by varying the composition of this gas. The maximum temperature of the surface of the cladding of specimens was estimated from measurements of the temperature of the cladding at a point approximately 200 C below the maximum. The initial tests of this design indicated that several improvements could be incorporated in future experiments.

WJZ:JWR/cc

APPENDIX A

HEAT-TRANSFER ANALYSIS

APPENDIX A

HEAT-TRANSFER ANALYSIS

Cladding configurations, and full-scale capsule sections, were evaluated using a two-dimensional, finite-difference digital computer program (2D-HEAT) developed at Battelle to calculate temperature profiles in a combined axial-radial heat-flow situation. The program included heat transfer by conduction and radiation. The r-z geometry option for symmetric configurations was used for these studies; x-y flexibility was also built into the program. The program was developed to handle problems of heat transfer through inhomogeneous and irregular bodies with nonuniform heat generation. Physical inhomogeneities were handled by dividing the section of interest into as many as 100 regions of different thermal conductivity, heat generation rate, and boundary conditions. Solids, gases, and vacuums were considered as regular regions; no limit was set on the number of gas-filled or evacuated annuli that could be used in a single problem. There was also no limitation on the number of boundaries (insulating, constant temperature, or convective) which could be used in a particular problem. A rectangular mesh of intersecting lines was imposed over a schematic model of the system to be analyzed, and the interval between mesh lines was varied as necessary to divide the model into desired regions. The mesh intersections were referred to as nodes.

A set of finite-difference equations applicable to the problem was based on the expression for heat conduction with volumetric heat generation. The basic two-dimensional heat conduction equation for the r-z geometry is:

$$-k \frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2} = q \quad , \quad (A-1)$$

where

k = thermal conductivity

T = temperature

q = heat generation rate

r = radial dimension coordinate

z = axial dimension coordinate.

The units of all terms were consistent. The specific-difference equations were derived for all nodes subject to continuity conditions with respect to temperature and heat flux at interfaces. Initially, the geometry of each node was identified. The proper set of specific-difference equations was assigned with proper substitution of finite-difference increments into the basic differential equations and applications of the finite-difference forms of the boundary conditions. These equations reduced to the same form:

$$A_1 T_{I, (J-1)} + a_2 T_{(I-1), J} + a_3 T_{I, (J+1)} + a_4 T_{(I+1), J} + a_5 T_{I, J} + A_{I, J} = 0 \quad , \quad (A-2)$$

where

a_i are constants associated with the geometry, thermal conductivity, and heat generation rate of the region

$T_{I,J}$ is the temperature associated with each node, $N_{I,J}$, in the mesh

$A_{I,J}$ is that part of the difference equations containing known constant-temperature terms including the radiative terms and heat generation rates.

The radiative heat gains and losses for each emitting and receiving node were calculated using the normal radiative heat-transfer equation modified with assigned view factors. The view factors accounted for heat transfer from each node (which represented one increment of a surface) to several incremental elements at various temperatures on a facing surface. Surfaces facing to the right and down were considered as emitting surfaces and those facing to the left and up were receiving surfaces.

While matrix inversion could have been used to solve the system of equations, the problem would have been cumbersome if a large matrix was used. Therefore, the relaxation or iterative successive-approximation method was employed. Values of constants and initial estimates of $T_{I,J}$ were assigned by including each mesh point in at least one region. The approximate heat-flow imbalance, H , was calculated at each node during each iteration. As each H was calculated, the temperature at each node was corrected by

$$T_n = T_{(n-1)} + \omega \frac{H_n}{a_5} , \quad (A-3)$$

where ω (greater than 1), the over-relaxation factor, accelerated the convergence. The subscripts n and $(n-1)$ refer to the n th and $(n-1)$ th iterations, respectively.

The error criterion, t , employed for the computation was expressed by

$$\frac{R_{(n-1) \max} \rho_n}{1 - \rho_n} < t , \quad (A-4)$$

where

$R_{n \max}$ = maximum residual at any node in the mesh

ρ_n = the value of a computed program parameter ($R_{n \max} / R_{(n-1) \max}$) which, if below a given input value, prevents a convergence check to avoid a false convergence.

The differences were established between the computer temperature at all mesh points and the corresponding temperatures arrived at from the previous iteration.

The method assumed that the approach to the solution was exponential. This was borne out in some simple problems. When this is the case, the error is expressed by

$$T_{\infty} - T_n = \left[T_n - T_{(n-1)} \right] \frac{\rho_n}{1 - \rho_n} \quad (\text{A-5})$$

or

$$T_{\infty} - T_n = \frac{R_{(n-1)} \max \rho_n}{1 - \rho_n} < t. \quad (\text{A-6})$$

Problems were run for a fixed number of iterations, after which the temperature matrix printout, the accuracy estimate, and the average temperatures for each region were inspected. Thermal conductivity inputs were corrected, if necessary, and the problem was restarted using temperatures stored on tape from the previous run. The problem was run until a credible convergence was obtained.

Although temperatures were calculated at every node, the program was utilized principally to determine (1) maximum temperatures based on expected fission heat rates in the Battelle Research Reactor (BRR), and (2) associated temperature gradients between this maximum and the proposed thermocouple locations. Initial computations for various configurations were made by allowing transfer of the fission heat to a constant-temperature sink (representing the capsule inner shell) through a vacuum or gas environment. When the final configuration was chosen, the complete radial and axial temperature profile from the centerline to the convective boundary at the exterior of the outer shell was computed for one section.

These solutions were obtained from idealized models. The program could not handle the asymmetrical effects of heat loss through thermocouple and support structure, or the partial baffle effect of several thermocouples passing through a zone to specimens located nearer the bottom of the capsule. Examination of these effects, however, indicated that they were negligible.

APPENDIX B

TEMPERATURE CONTROL SYSTEM

APPENDIX B

TEMPERATURE CONTROL SYSTEM

A variable gas-composition method was used to control the temperature of the specimens in this design. Basically, the relative amounts of nitrogen and helium flowing through the outer capsule annulus are varied to alter the thermal conductivity of the gas mixture and thereby change the inner-shell, or heat-sink, temperature. A flowing gas is used to prevent segregation of the gases which might occur in a static system.

The nitrogen and helium are supplied to the capsule from separate gas lines which merge at a tee in the lead tube approximately a foot above the capsule. With this arrangement there is a significant time lag from the initiation of a composition change until a new temperature is achieved. To accommodate this lag a relatively simple system is used whereby a corrective action (composition change) is made for a short time period followed by a period of time to allow the reaction (a new temperature equilibrium) to occur. The process or action followed by a time for reaction is repeated until the desired temperature is achieved.

The temperature-control instrument which monitors one thermocouple, has a 5 C null band on both sides of the control point. There is no corrective action called for within this null band. When the temperature is below the null band the controller actuates a motor-driven micrometering valve to increase the nitrogen content in the helium flowing through the capsule annulus. The 1-rpm motor drive on the valve is interrupted by a recycle timer so that the control action proceeds for 15 sec, then waits 285 sec for the reaction to occur. The interrupted action of the nitrogen valve is continued until the temperature reaches the null band. A similar process occurs, decreasing the nitrogen content, when the temperature exceeds the null band.

The controller provides other functions for purposes of safety. If the temperature exceeds the null band by 50 C, the nitrogen supply is closed and the flow rate of helium is increased to effect a rapid reduction of temperature. A reactor scram is actuated at the same temperature. A thermocouple failure will also actuate both of these functions. When the temperature drops below 1550 C, as during a reactor shutdown, the nitrogen-to-helium ratio of the gas flowing in the annulus is held fixed. Before reactor operation is resumed a manual override is used to close the nitrogen control valve so that the control action will proceed from a low temperature to the null band rather than exceed the desired temperature. The manual override also provides a means for making rapid adjustments in temperature.

APPENDIX C

STRANDED THERMOCOUPLES

APPENDIX C

STRANDED THERMOCOUPLES

To evaluate the accuracy of the predictions of the thermal analysis, it was necessary to place a thermocouple on the surface of the cladding to obtain a direct measurement of the maximum temperature. The use of sheathed thermocouples was precluded and an open-end-sheath, bare-wire unit was also eliminated on the basis of probable loss of insulation. Practical experience with the use of bare-wire tungsten-rhenium thermocouples in this application was very limited. Spot welding techniques have been used extensively to attach thermocouple wires to surfaces at low temperatures (<800 C). However, it was not desirable to spot weld refractory elements to the specimen surface; the thermoelements would be embrittled and prone to failure before the start of the experiment and there was a danger of localized damage to the cladding. In addition to the problem of obtaining surface contact, there was the additional problem of obtaining a reliable junction with rather inflexible 0.010-in. -diameter wires.

It was found that flexible thermocouples could be made by stranding small-diameter wire⁽¹⁾. Commercial, calibrated 0.003-in. -diameter (0.0076 cm) wire (tungsten-5 w/o rhenium versus tungsten-26 w/o rhenium) was obtained. Each leg of the thermocouple was formed from eight strands of 0.003-in. -diameter (0.0076 cm) wire twisted together in a spiral with a hand drill. The thermocouple junction was made by tying a square knot in a pair of strands. The knot was then secured to the surface of a specimen with stranded tie-wires. The stranded wires were sleeved with 1/16-in. -diameter (0.159 cm), two-hole [1/64 in. diameter (0.040 cm)], high-purity BeO protection tubing in the hot zone and with 6 ft (1.83 m) of alumina tubing from the header into the lead tube. The ceramic tubings of individual thermocouples were encased in 1/8-in. -OD (0.318 cm) stainless steel tubes above the header. The lower end of each stainless steel casing extended a short distance into the inner shell, and these tubes were brazed into the interior of the header at their point of exit. A fission-gas seal was made by mounting the bare wires, ceramic, and tubing in epoxy resin at the upper end of each casing. Thus, these resin seals become part of the primary fission-product containment and the capsule lead tube was part of the secondary containment.

Prior to assembly, all components were cleaned with detergent, acetone, and 200-proof alcohol in successive steps. The ceramic insulators were baked in air at 450 C to oxidize any contaminants present. The assembly of specimens and the attachment of thermocouples were accomplished with lint-free nylon gloves to prevent hydrocarbon contamination of surfaces.

(1) Chenault, W. S., GE-NMPO, Cincinnati, Ohio, Personal visit, March 22, 1966.