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INSTRUMENTED TEMPERATURE-CONTROLLED CAPSULES FOR IRRADIATIONS IN THE CP-5 REACTOR

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ARGONNE NATIONAL LABORATORY
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Metallurgy Division

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ABSTRACT

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INTRODUCTION

The development of fuel materials for reactors is generally accompanied by an evaluation program in which the experimental fuel material is irradiated under various high-temperature and burnup conditions. These experiments can be performed by utilizing suitable capsules, containing representative configurations of the fuel, which are introduced into a reactor irradiation facility. Subsequent postirradiation examination and measurements of the specimens serve to establish the operation behavior of the fuel under study.

In performing a meaningful irradiation experiment it is essential that the desired fuel temperature be maintained throughout the irradiation period. For that reason the design of the capsule must be such that the temperature can be continuously monitored, and means must be provided whereby the temperature can be controlled. From experience gained by study of several hundred uninstrumented capsules irradiated in the MTR and ETR reactors,(1) a capsule configuration was adopted which was suitable for conversion to a thermocouple-instrumented, resistance heater-controlled experiment.

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CP-5, a heavy water-cooled and moderated research reactor located at the Illinois site of Argonne National Laboratory, was selected as the most suitable reactor in which to irradiate the capsules. The CP-5 reactor has vertical thimbles located within the fuel tubes. These thimbles offered an irradiation facility which, with certain modifications, would be suitable for dissipating large quantities of heat. In addition to this, the close proximity of the reactor made it readily accessible to operating personnel and thus would facilitate the operation of several experiments at one time.

The fuel thimbles and shield plugs were first modified in order to accommodate the capsule experiments. Instrumented capsules were then built and inserted into the reactor. The modifications to the reactor have been previously reported.(2) This report describes the development of the capsule program and the operational characteristics of the capsules, as well as the components.

DESCRIPTION OF THE CP-5 RESEARCH REACTOR

The CP-5 reactor(3) is a heavy water-moderated and cooled research reactor (see Figure 1). The reactor tank is 6 ft in diameter and 9 ft 7 in. in height. It is fueled with cylindrical tubular elements of aluminum-uranium alloy jacketed with aluminum. The complete core loading constitutes 17 vertical fuel elements, each element consisting of three concentric fuel tubes. Access ports and columns have been provided at strategic points to serve as irradiation facilities in the reactor. These facilities include (1) vertical D_2O thimbles, (2) vertical graphite thimbles, (3) thermal column, (4) horizontal beam holes, and (5) isotope tunnel.

The vertical fuel elements, one of which is illustrated in Figure 2, are suspended in the reactor vessel. Heavy water is pumped into a distribution plenum at the bottom of the tank and passes through an orifice in the bottom of each of the fuel elements. Inserted in the inner fuel tube is a thimble, the lower end shaped into a tapered cone which serves as a deflector, distributing the heavy water to the fuel tubes. Inside the thimble there is normally located an air-cooled thimble liner in which isotope irradiations are performed which do not yield significant amounts of heat.

When reviewing possible irradiation facilities in the CP-5 reactor for instrumented capsules, preference was given to the vertical fuel tubes, which were readily accessible, provided the highest neutron fluxes, and offered a means of dissipating large quantities of heat. By the modification of the fuel thimble, a metered amount of heavy water could be diverted into the thimble cavity for cooling a capsule.

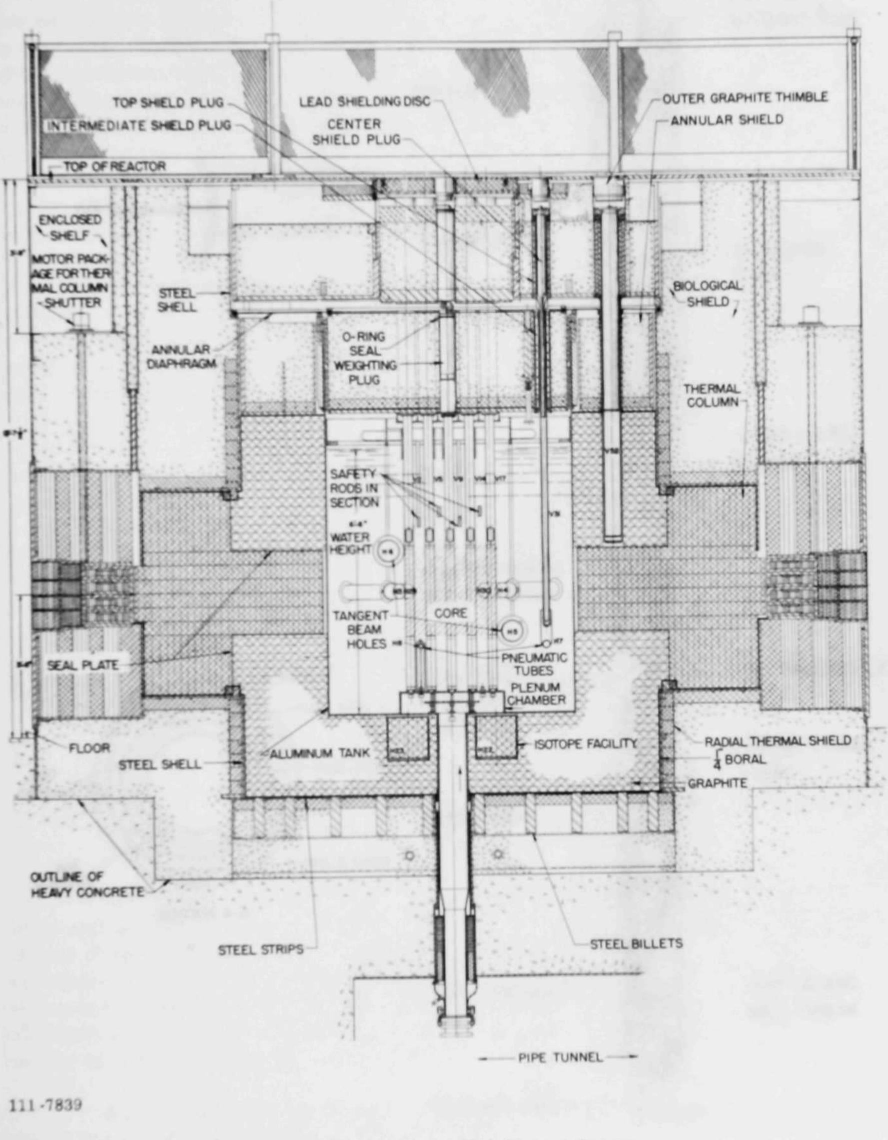

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Figure 1. Elevation of CP-5 Research Reactor

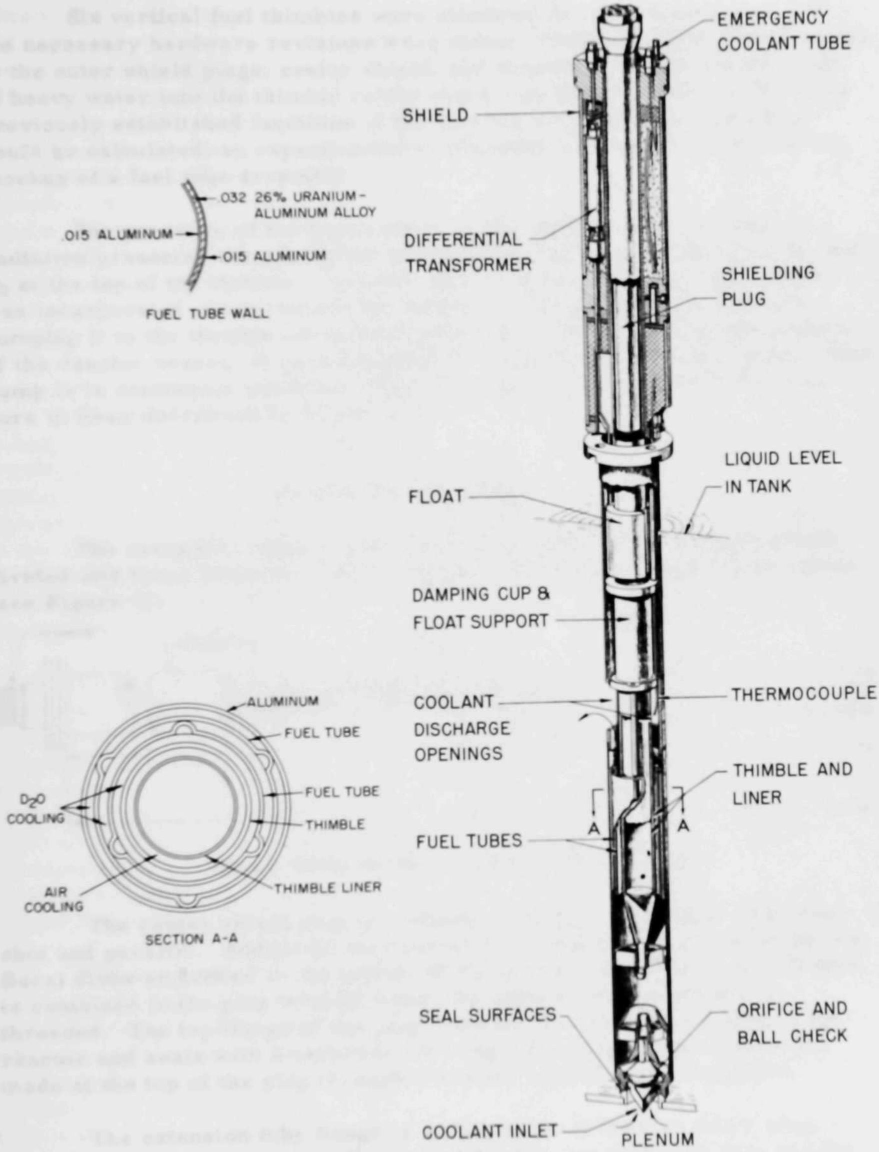

Figure 2. CP-5 Cylindrical Fuel Element before Modification

Six vertical fuel thimbles were allocated for the experiments and the necessary hardware revisions were made. These included modifications to the outer shield plugs, center shield, and thimbles.(2) The introduction of heavy water into the thimble cavity was a significant departure from the previously established functions of the thimble and, although flow rates could be calculated, an experimental verification was made in a full-scale mockup of a fuel tube assembly.

The presence of the heavy water in the thimble cavity during irradiation presented the possibility of trapping explosive mixtures of D_2 and O_2 at the top of the thimble. To avoid this hazard a helium purge system was incorporated which utilized the reactor reservoir supply of helium, pumping it to the thimble cavity and exhausting it to the helium atmosphere of the reactor vessel. A parallel coupled two-pump system is utilized. One pump is in continuous operation while the other operates only if the pressure in lines decreases by 50 per cent.

CAPSULE ASSEMBLY

The complete capsule assembly is approximately 9 ft long and is divided into three sections: center shield plug, extension tube, and capsule (see Figure 3).

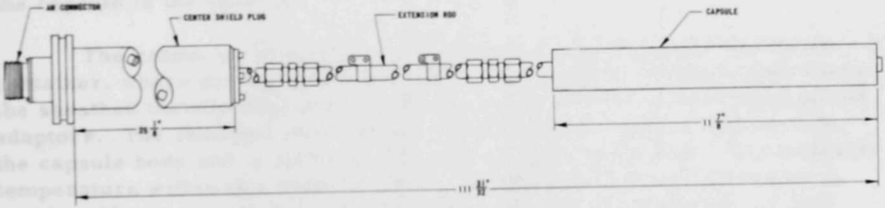

Figure 3. Irradiation Capsule Attached to Center Shield Plug

The center shield plug is a stainless steel casing filled with lead shot and paraffin. Additional thermal neutron shielding is provided by two Boral disks embedded in the bottom of the casing. A spiral, $\frac{1}{2}$-in.-ID tube is contained in the plug through which the capsule wiring harness is threaded. The top flange of the plug seats on the outer shield plug in the reactor and seals with a neoprene "O" ring. Electrical connections are made at the top of the plug through a sealed, multiple pin receptacle.

The extension tube flange is bolted to the bottom of shield plug. This $\frac{3}{4}$-in.-OD, 2S aluminum flange is joined to the extension tube proper ($\frac{5}{8}$-in.- OD aluminum) with a Type 304 stainless steel Swagelock reduction fitting. Between the flange and the shield plug, a $\frac{1}{8}$-in.-thick cadmium plate has been incorporated as a thermal neutron shield to prevent the

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DESCRIPTION OF CAPSULE

The capsule is a cylinder, 1-$\frac{1}{2}$ in. in diameter, which may vary in length from 13 to 29 in. depending upon the size and placement of the irradiation specimens. It is divided into two main compartments - the connector housing, and the specimen container. An exploded view of a typical capsule is shown in Figure 4. Spacer studs, $\frac{1}{16}$ in. high, are welded to the outer surface of the capsule which center the tube within the reactor thimble and maintain the water-cooled annulus. A clearance of $\frac{1}{32}$ in. is maintained between the studs and the thimble wall to facilitate insertion of the capsule in the thimble.

The connector housing is a sealed enclosure above the specimen container, where electrical connections to the heaters are made and where the sheathed thermocouples are joined to flexible leads in individual potted adaptors. The chamber is fabricated of material similar to that used for the capsule body and is joined to the capsule by a seam weld. The ambient temperature within this housing during irradiation has been measured to be 30 to 35 per cent of the mean temperature rise of the sodium or NaK surrounding the specimens. All insulation material used within the chamber is inorganic and capable of withstanding prolonged irradiation at temperatures up to 500°C.

The specimen container encapsulates the experimental specimens, thermocouple junctions, auxiliary electrical heater, and a heat transfer medium which is generally NaK. The cylinder wall may be solid one-piece construction, duplex tubing in tight contact, or two tubes separated by circumferential fins. The selection of the particular configuration of capsule body is dependent upon the desired irradiation temperature of the specimens. Duplex tubing is preferred over a single wall for safety reasons, for failure of one of the tubes will not open the capsule contents to the reactor coolant. The duplex tubing that has been used is not metallurgically bonded but consists of two tubes in intimate contact. This contact is attained by drawing the tubes together to 0.015 in. undersize. The tubes are bottom of the shield plug from becoming highly radioactive after prolonged and repeated exposures to the reactor flux. The extension tube houses the wiring originating from the capsule, and the length of tube is varied to position the capsule within a desired flux region in the reactor fuel tube. An eye clip is fastened to the tube 12 in. above the top of the capsule. When the experiment is removed from the reactor, a cable is attached to the clip and the extension tube is severed. The capsule may then be easily transferred to a shielded container and then into a shielded cell. The extension tube is connected to the capsule by a second Swagelock which necessarily must be water-tight, as it is located below the D_2O level in the reactor vessel.

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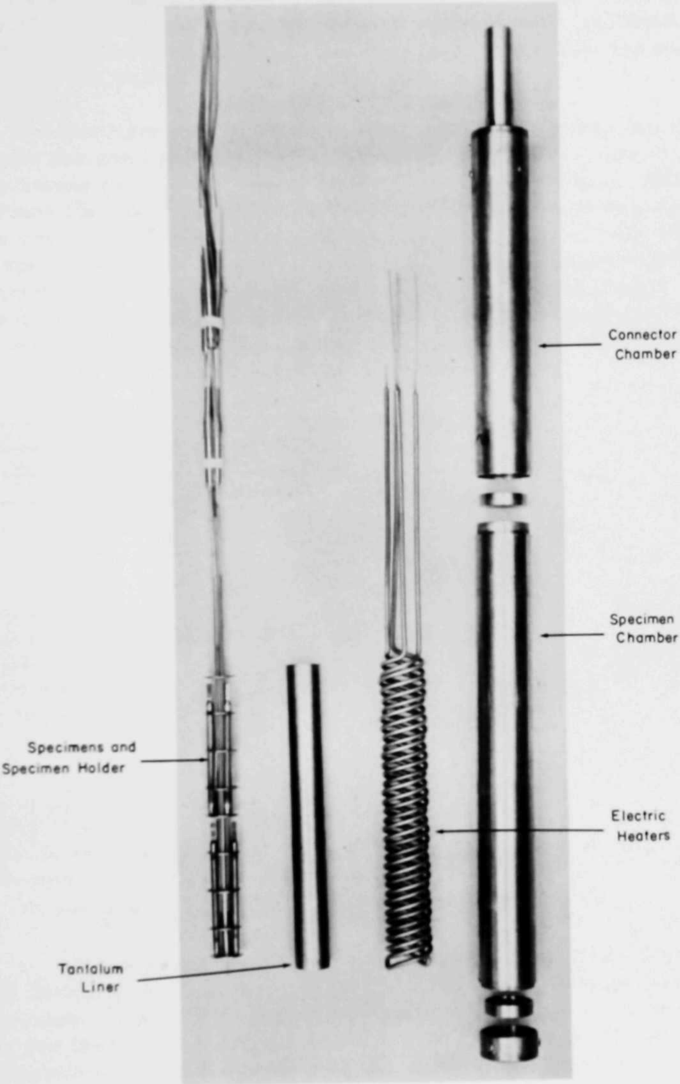

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Figure 4. Disassembled View of Typical Capsule Components

then sized by expanding with no restraint on the outside diameter to the specified 1.5-in. OD. The assembled tube is stress relieved and annealed at 650°C. The drawing operation is performed without the use of lubricant between the walls.

Heat transfer barriers in the form of fins have also been used. These are used primarily when irradiating structural materials or fuel specimens producing comparitively low amounts of heat. Diagrams of the various fin spacings that have been used are shown in Figure 5. The fins are cut into the outside diameter of the inside tube. A drawing operation is applied to assure that the fins make intimate contact with the inside diameter of the outside tube. Measurements of temperature scalloping along the length of the tubes showed that, at an average distance of 0.03 in. away from the inside capsule wall, the variation was less than 2 per cent.

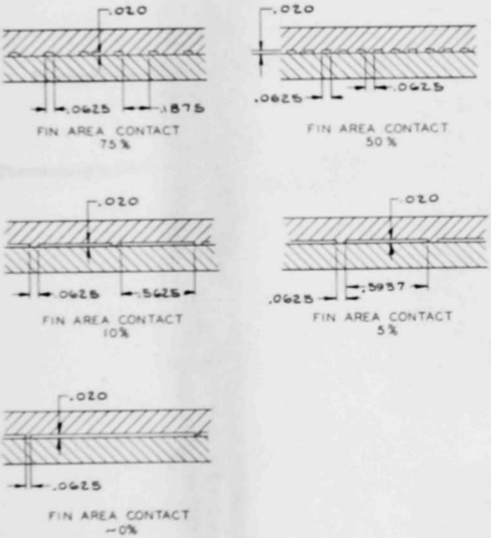

Figure 5

Fin Area Contacts Tested in Double-wall Capsules. The Annulus between Fins Is Filled with Helium.

The materials used for capsules have been Type 304 stainless steel and Zircaloy-2. The majority of irradiations performed have been with Zircaloy-2 capsules. The preference for Zircaloy-2 was due primarily to the low thermal neutron-absorption cross section of the material and better compatibility with the metallic fuels undergoing irradiation.

One fuel, however, which revealed a tendency to attack Zircaloy-2 is uranium-20 w/o plutonium-10 w/o fissium alloy. In capsules containing this fuel material a 0.010-in.-thick tantalum cup has been incorporated inside the heater windings, which insertion isolates the specimen holder from the capsule body. All capsule parts are joined by inert-gas-shielded tungsten electrode welding. No filler metal is added.

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The specimens in the capsule are mounted in holders which limit excessive vertical and lateral motion, yet provide a margin of clearance for possible swelling of the fuel. The majority of irradiations have been conducted on cylindrically shaped specimens; however, the capsule will also serve to irradiate materials of a variety of different shapes. The specimens are located three to a tier so that three specimens are at the same vertical elevation within the capsule. This arrangement has proven valuable in comparing the irradiation characteristics of different materials under essentially identical irradiation conditions, for the temperatures and neutron flux at the same elevation are relatively uniform.

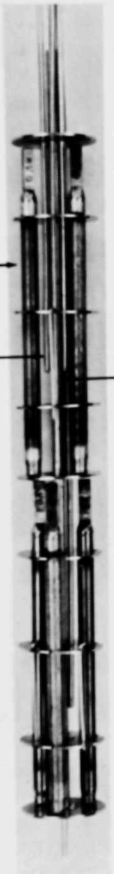

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Figure 6. Two-tier Disk-type Specimen Holder with Jacketed Fuel Specimens

Figure 6 shows a typical specimen holder assembled with two tiers of specimens. The holder consists of an assembly of stacked disks which support and position the specimens, 120° apart, in holes drilled through the disks. Additional holes in the disks serve to position accurately the temperature-measuring thermocouples and monitor wires for flux measurement. The monitor wires are strung longitudinally between specimens, on the same radius passing through the center of the specimens. The holders are fabricated of 0.025-in.-thick Zircaloy-2. The spacers of the disk holder which normally do not come in contact with the fuel are Type 304 stainless steel.

The type of materials which have been irradiated include both structural and fuel materials. The fuel specimens are cylinders approximately 0.144 in. in diameter and one to two inches long. They have been both clad and unclad. In some instances with clad uranium fuel the cladding was open at the top. Plutonium fuel specimens have always been completely clad. In many of the uranium specimens an axial hole was drilled half the length of the fuel, and a thermocouple was inserted for direct measurement of central fuel temperatures.

Auxiliary temperature control is provided in the capsules by electrical resistance heaters. The elements are stainless steel-sheathed Nichrome-V or Kanthal wire insulated with magnesium oxide. The element is wrapped into a coil which encircles the specimen holders. At the topmost convolution of the heater, the Nichrome or Kanthal is joined to a nickel conductor. This procedure is used to maintain the heat-generating portion of element below the NaK level in the capsule. By so doing, it is possible to operate the element at higher surface heat fluxes than the normal in-air rating. Another consideration was to alleviate the necessity of dissipating additional heat in the connector chamber. The first heaters were $\frac{1}{16}$ in. in diameter. The life expectancy of these units was unpredictable and usually quite short. The predominant failure arose from arcing from the nickel conductor to the sheath at the point where the bare wire emerged from the sheath. Contamination of the magnesium oxide was suspected, and attempts to reinforce the electrical resistance wire at this point were made without substantially prolonging the operational life. The diameter of the heater was then increased to $\frac{1}{8}$ in., and the failure rate decreased by 60 per cent. Sealing the exposed magnesium oxide with a porcelain glaze and storing the units in a moisture-free environment was found to extend the shelf life of the heaters. The elements are rated for 1000 w at 110 v. Similar units with 3000-w rating have also been used. Two parallel-wound 1000-w heaters have proven effective in controlling the capsule temperature, with the additional safeguard that, in the event of failure of one heater, the other can maintain the irradiation temperature. The spacing of the convolutions of the heaters must be taken into consideration in determining the temperature profile of the capsule as well as the auxiliary heat-flux density. This spacing may be used to advantage in that the convolutions may be adjusted prior to capsule assembly as a minor correction to the temperature profile.

Flux monitors in the capsules are used to obtain preliminary integrated flux values for calculating fuel burnup. The alloys from which monitor wires have been fabricated are aluminum-cobalt, manganese-cobalt, and nickel-cobalt. Diameters of the wires have varied from 0.010 in. to 0.035 in., and the cobalt content was varied from 0.066 to 0.7 per cent. The cobalt concentration is preselected on the basis of an anticipated radiation intensity of $\frac{1}{16}$-in. segments of the wire. The aluminum-cobalt wires are used in capsules in which the central fuel temperatures will not exceed 650°C. The nickel-cobalt wires have been used in capsules in which central temperatures have been as high as 1000°C. The manganese-cobalt wires in NaK or sodium tend to undergo a dissolution process in an ambient temperature above 500°C, and for that reason their application has been limited to low-temperature irradiations.

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The temperature of the connector chamber was measured in several capsules in order to determine maximum operating conditions for insulating materials and adhesives.

Within the specimen chamber, the sodium or NaK temperatures have been measured at the following positions: adjacent to the specimen on the centerline of the fueled portion, along the length of the specimen in order to determine the vertical temperature profile, between two specimens, and predetermined distances from the specimens to the capsule wall. The majority of measurements which serve to establish central specimen temperature are taken from thermocouples located adjacent to the specimens on a radial line between the center of the capsule and the center of the specimen. This location is preferred because the profile of the temperature distribution in the capsule is such that the thermocouple may be misplaced as much as 0.1 in. with a resultant maximum error of only 3 per cent in determining the central fuel temperature.

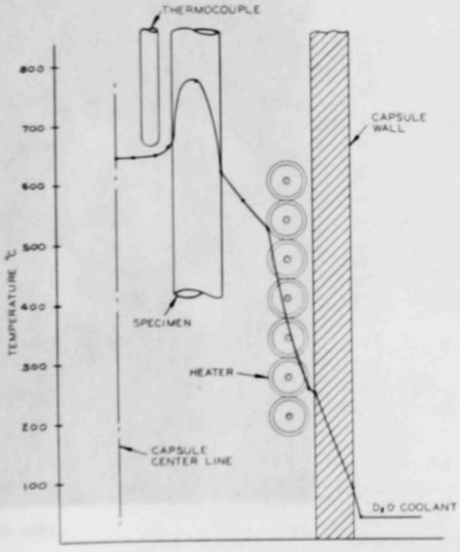

Figure 7. Temperature Distribution through Fuel Element Irradiation Capsule. Only One of the Three Specimens in the Tier Is Shown.

The temperature distribution within the capsules is determined by calculation, electrical analogue,[4] and direct thermocouple readings. A profile of temperature distribution within a typical capsule is shown in Figure 7. Specimens have been used with axial 0.043-in. holes drilled half the length of the specimen. A 0.040-in.-diameter sheathed thermocouple was inserted in this hole, and a verification of the analogue data was made.

Thermocouples used in the experiments are a $\frac{1}{16}$-in.-diameter sheathed immersion type with chromel-alumel calibration and a potted transition to the lead wires. The operating temperature range in the capsules is normally below 1000°C, and for that reason the chromel-alumel wire has proven satisfactory. In addition, this temperature measurements have been taken are: (1) within the connector chamber, (2) sodium or NaK in the capsule, and (3) center regions of the fuel specimens.

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couple has not demonstrated a tendency toward irradiation-induced emfs and has retained its calibration after being in continuous service for over a year. The sheathing material specified is usually Type 304 stainless steel. Tantalum-sheathed thermocouples, 0.040 in. in diameter, have also been used for central fuel instrumentation. Quality control of the tantalum sheath material was a problem as was also obtaining a satisfactory braze between tantalum and the Zircaloy-2 capsule cap. The present approach is to utilize Type 304 stainless steel-sheathed thermocouples which are plated with 0.002 in. of tantalum metal. This plating covers the sheath from the hot junction of the thermocouple to a position just above the NaK level in the capsule.

Potted transitions, which are located in the connector chamber, alleviate the necessity of threading semirigid sheathed conductors through the extension tube and shield plug. Twenty-four-gauge solid lead wires, insulated with a double covering of Fiberglas, are welded to the sheathed thermocouple wires. Potting compounds found to be satisfactory for this application are Sauereisen No. 29 or No. 31.

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Figure 8

Top Cap of Capsule Showing Thermocouples and Heaters Brazed to Zircaloy with ANL-11 Alloy.

The thermocouples are introduced into the specimen chamber through holes drilled in the top cap. Brazing of thermocouples and heater leads is performed in one operation with an induction welder and in a controlled atmosphere. A photograph of a typical cap after brazing is shown in Figure 8. ANL-11 alloy[5] is used to braze the stainless steel-sheathed thermocouples in the Zircaloy-2 caps. This alloy has the composition zirconium-8 w/o nickel-8 w/o chromium and has a melting point near 900°C. It is compatible with sodium and NaK, and is corrosion resistant to water.

In brazing 0.040-in.-diameter thermocouples to the cap, quite frequently the sheath would be perforated. To avoid this defect, protective sleeves, having a wall thickness of 0.020 in., were swaged over the thermocouple at the region where the braze had to be made. The sleeve was initially brazed to the thermocouple and tested before it was brazed to the cap. An improvement to this procedure was the development and adoption of a standard $\frac{1}{16}$-in.-OD thermocouple with the last inch or inch

and a half swaged to a diameter of 0.040 in. This permitted a cap braze to a $\frac{1}{16}$-in.-diameter sheath of sufficient thickness, yet provided a means of measuring center fuel temperatures. The first units tested in capsules were fabricated at Argonne facilities. Commercial sources are presently available for this type of thermocouple.

The thermocouple life expectancy in this application is limited by the thermal shock resistance of the individual thermocouple. Ninety-six per cent of all failures have been attributed to thermal shock. Whenever the CP-5 reactor "scrams," the capsule temperatures drop to the reactor coolant temperature within a period of 2 to 3 sec provided electrical heating is not being used. During some irradiations, over 500 thermal shocks have been recorded. Bench tests, simulating thermal shock conditions in the reactor, have been conducted on thermocouples of six major manufacturing concerns. The overall average number of thermal shocks that the thermocouples could withstand was 156. The lowest value was one and the highest 630. The failure within units fabricated with a hot junction grounded to the sheath is generally a separation of one of the wires from the junction. On units having ungrounded hot junctions, the wire may separate at the junction or anywhere along the length which has been heated. Increasing the diameter of the thermocouple or the size of the wire has not improved the thermal shock resistance.

Organic thermocouple insulations have been evaluated inside of connector chambers at temperatures of 175°C and thermal neutron fluxes of 5×10^{13} n/sec. The effect of these conditions on a nylon covering was a complete separation from the thermocouple wires. Fused Teflon embrittled and flaked off the wires. Polyvinyl Nylon became very brittle and cracked, but adhered to the wire. Inorganics, such as Fiberglas over Fiberglas and Fiberglas over asbestos, suffer discoloration and become brittle but do not lose their electrical resistivity to a point where it affects the thermocouple calibration.

The extension leads of the thermocouples as well as the heater wires are grouped in the connector chamber and fed through the extension tube and the shield plug. The ends are soldered to a multipin sealed receptacle. Compensating chromel and alumel material is used in the assembly of matched pairs of pins. The insulating material of the receptacle is silicone rubber. The bottom surface of the insulating material is continuously exposed to the reactor environment, the major constituent being helium. Prolonged exposure to the reactor environment tends to embrittle and crack the silicone rubber. The rate of deterioration has been noted to be approximately 0.010 in. per month; however, over a period of 14 months the receptacle remained pressure-tight.

Extension cables, 60 ft in length, connect the shield plug to the temperature instrumentation located in the basement of the reactor building.

The matched pairs of thermocouple compensating lines are 14-gauge wire covered with 0.040 in. of polyvinyl insulation. The shielded cables terminate at one end in a matching screw thread receptacle, which mates the connector on the shield plug, and at the other end to a terminal board in the instrument cabinet. Four copper conductors are included for the capsule heaters. The bundle of wires is encased in a shielded braid as a protection against abrasion.

Temperature read-out is by 16-point strip chart recorders (see Figure 9). Each recorder is equipped with an over-temperature limit switch which is connected to the scram circuit of the reactor. The scram set point can be adjusted and is selectively positioned to temperatures critical to the integrity of the specimens. Also incorporated into this circuit is a provision whereby an electrical power loss within the instrument cabinets will automatically shut down the reactor. If one of the thermocouple readings on the multipin recorder scrams the reactor, the chart and pen motions immediately lock in position, thereby permitting rapid and accurate identification of the thermocouple and capsule indicating an over-temperature condition.

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Figure 9. Controllers and Recorders Installed in the Basement of the CP-5 Reactor for Operation of Irradiation Experiments in Five Vertical Thimbles.

Each capsule is provided with a minimum of six thermocouples. Failure of these thermocouples has not been deemed as a condition necessarily requiring shutting down the reactor or removing the capsule. For that reason, the thermocouple-break provision within the recorders has been eliminated, so that a thermocouple failure will not cause the pen to travel upscale and trip the scram circuit.

One of the thermocouples in each capsule is connected to a separate millivoltmeter high-limit controller. This instrument is utilized as a temperature warning device and is preset to actuate at a temperature slightly higher than the control irradiation temperature. When this controller is tripped, a warning light will be displayed on the control panel of the capsule experiment as well as on the panel in the reactor control room. If the thermocouple connected to the instrument fails, the warning light is actuated. A bypass relay circuit with a key lock switch permits clearing the warning light in the control room until the faulty thermocouple can be replaced.

The resistance heaters in the capsules are operated with saturable core reactors controlled from a millivoltmeter-type controller. A rheostat was incorporated into the system to preset selectively a maximum wattage input to the heaters. Shunt resistances, in the form of pushbutton switches, are tied across the output legs of saturable core reactors to suppress line surges. This shunt is used to short out the resistance of the heater at the moment the power switch is turned on. The instantaneous line surge can at times be of sufficient magnitude to arc across the heater in the capsule. Once the main power switch is on, the arc-suppression switch is released.

The effective range of temperature control of the capsules with resistance heaters is dependent upon the ratio of the available auxiliary heat to the heat developed in the specimens by fission. As this ratio decreases, the desired irradiation temperature of the specimens must be approximated by capsule design independent of the use of the heater. The auxiliary heat then serves to compensate only for minor flux variations within the reactor core.

With the saturable core reactors it has been possible to maintain a desired central irradiation temperature of ±2.5°C over extended periods of time. It has not been possible to introduce sufficient auxiliary heat to maintain temperature during the reactor shutdowns with the specimen loadings that contain sizable quantities of fissile material.

PREIRRADIATION INSPECTION AND TESTS OF CAPSULE AND COMPONENTS

Special consideration had to be given to safeguard against the possibility of capsule failure while in the irradiation facility. A series of tests were established which were designed to simulate the capsule behavior in the reactor. Material-inspection procedures were adopted to eliminate imperfect or questionable components. Double containment of the NaK was deemed necessary as well as providing a means of detecting a failure of one of the containments.

The stock material of which the capsules are fabricated is subjected to a careful visual examination for defects. The material is then machined to size and an eddy current, point probe technique is used to locate cracks exceeding 0.002 in. in depth. The capsule body, which constitutes two separate tubes in intimate contact, is subjected to an X-ray inspection as well as an eddy current test of the inside and outside surfaces. A grooved separation exists between mating surfaces of duplex tubing which, in event of failure of one of the tubes, permits the passage of NaK or D_2O to a sealed chamber at the bottom of the capsule. The failure is detected by the localized change in temperature in the sealed chamber.

All welds are subjected to a helium leak check with a mass spectrometer. The thermocouples are X-rayed, tested for leaks with a mass spectrometer and calibrated before and after being welded into the top cap. The completed capsule assembly, which includes the extension tube, is pressure checked at 90 psi. This ascertains that the secondary container which is in direct contact with the reactor coolant is leak tight.

The proper placement of components within the capsule as well as the NaK level is determined by an X-ray inspection. The capsule is then operated in a test stand at intended irradiation temperatures. While at this temperature, the capsule is vibrated for one hour to insure proper wetting of the NaK to all contacting surfaces. While the capsule is at the desired operating temperature the thermocouples are also checked for calibration, and the NaK level is again determined by X-ray radiography.

The top shield plug is attached and the thermocouples are again checked with the auxiliary heat source in operation. This same procedure is repeated when the capsule is inserted into the vertical thimble of the reactor, before the reactor is brought to power.

POSTIRRADIATION HANDLING OF THE EXPERIMENT

The irradiated capsules are handled in a cylindrical transfer cask measuring 16 in. in diameter and 5 ft in length. A 4-in. axial hole extends

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POSTIRRADIATION HANDLING OF THE EXPERIMENT

The irradiated capsules are handled in a cylindrical transfer cask measuring 16 in. in diameter and 5 ft in length. A 4-in. axial hole extends the full length of the cask, which is closed at both ends by shielded gates. The procedure in removing a capsule from a vertical thimble is to position the cask vertically over the thimble, and withdraw the 9-ft capsule assembly through the cask until the capsule containing the specimens is above the lower gate. This gate is then closed and a 20-ft steel cable is clipped to the recovery bracket on the extension tube. With the use of bolt cutters, the extension tube is severed immediately above the extension tube bracket. The capsule is then lowered by means of the attached cable to the bottom of the cask, and the top gate is closed. The cask is transferred to the face of a shielded cell, and the same cable serves to pull the capsule into the cell.

Prior to opening the capsule, a pinhole autoradiograph is taken.(6) This serves to establish the location and condition of specimens. The amount of loose radioactive material at the bottom of the capsule can also be determined.

The capsules are opened with a vertical lathe. The top chamber is first separated, and the thermocouple leads as well as the heater junction are cut. The specimen chamber is then cut just below the top cap. The entire assembly, which includes heaters and specimen baskets, is then removed from the NaK. The NaK is dissolved off the assembly with butyl alcohol, and the specimens are removed for a postirradiation examination.

The capsules are opened in a hood within the hot cell in which is maintained a nitrogen atmosphere having an oxygen content of less than $\frac{1}{2}$ per cent. This precaution precludes the possibility of excessive oxidation or fire which would damage the specimens.

PERFORMANCE CHARACTERISTICS OF THE CAPSULE

The capsule irradiations have been conducted in the thimbles in the center ring of reactor fuel elements. These vertical thimbles are designated as VT-4, -5, -8, -10, -13, and -14. The experiments have been performed under conditions of varying reactor power as the established operating level was raised in stages from 2 to 5 Mw. The neutron flux within the thimbles was found to be relatively linear with the increases in reactor power levels. Design of the various capsules was dependent upon the heat generation of the specimens, which for reactor powers near 2 Mw required the use of gas annuli to attain desired irradiation temperatures.

The types of gas annuli (that is, the fin spacings) tested have been previously described. A graph comparing these annuli in terms of reactor power versus indicated central fuel specimen temperatures is shown in Figure 10. The curvature of the lines, which is accentuated as the fin contact area is decreased, follows the expected variations in heat transfer characteristics of this configuration, which is also discussed in reference 7.

the full length of the cask, which is closed at both ends by shielded gates. The procedure in removing a capsule from a vertical thimble is to position the cask vertically over the thimble, and withdraw the 4-ft capsule assembly through the cask until the capsule containing the specimens is above the lower gate. This gate is then closed and a 20-ft steel cable is clipped to the recovery bracket on the extension tube. With the use of bolt cutters, the extension tube is severed immediately above the extension tube bracket. The capsule is then lowered by means of the attached cable to the bottom of the cask, and the top gate is closed. The cask is transferred to the face of a shielded cell, and the same cable serves to pull the capsule into the cell.

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The capsules are opened in a hood within the hot cell in which is maintained a nitrogen atmosphere having an oxygen content of less than ½ per cent. This precaution precludes the possibility of excessive oxidation or fire which would damage the specimens.

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This is due to the relationship of the thermal conductivity of the heat transfer mediums to the specific temperatures. Zircaloy-2 capsules filled with NaK and without a gas annulus maintain a near-linear relationship between heat generation and irradiation temperature. If sodium is substituted for the NaK, the variation of sodium conductivity with temperature will be noted.

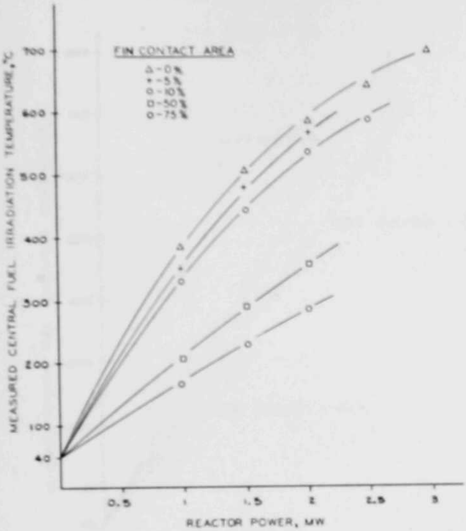

Figure 10. Measured Central Irradiation Temperatures in 0.144-in.-diameter, 10% Enriched U-5 w/o Fs Alloy Specimens Versus Reactor Power for Various Fin Contact Areas.

The use of sodium instead of eutectic NaK as a heat transfer medium provides distinct advantages in terms of thermal conductivity. However, once a capsule loaded with sodium is inserted into the reactor, the auxiliary heat source must be capable of maintaining the metal in a molten state while the reactor is not operating. The repeated freezing and melting of this volume of sodium with resultant volume changes will exert considerable force on the specimen holder and specimens. In some cases this has resulted in appreciable movement of specimens and damage to the holders within the capsule.

A comparison of irradiation temperatures versus reactor power for three basic fuel specimen enrichments is shown in Figure 11. An increase in fissile material does not yield a proportionate increase in heat generations. This is due to the increased fuel specimen perturbation, which lowers the effective flux within the specimen.

In irradiating capsules in the CP-5 reactor, consideration must be given to the sizable resonant neutron flux present in the fuel thimbles. The vertical profile of the resonant flux does not match that of the thermal neutron flux. For this reason, positioning of the capsule within the 24-in. fuel tubes is critical in terms of heat generation. During reactor startup, the control rods are normally withdrawn to a position which happens to produce a peak in the thermal flux near the top 6 in. of the fuel tubes. After xenon burnout in the core, the rods are reinserted so that after approximately 30 hr a normal flux profile exists within the fuel tubes. The neutron flux 6 in. on either side of the midplane of the core is not generally affected by this control rod motion. The neutron fluxes within the center ring of vertical thimbles used for the capsule irradiations has been found

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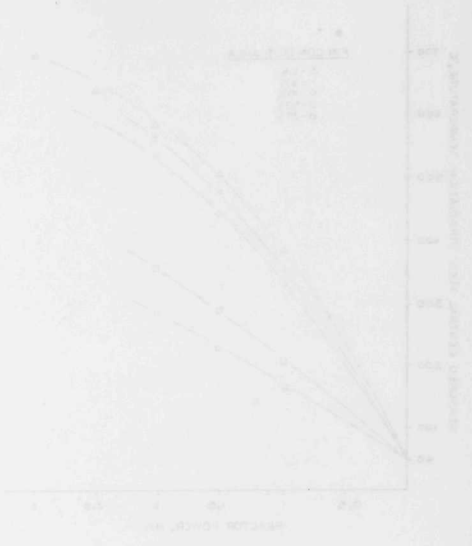

Figure 16. Measured Central Irradiation Temperature in 0.444-in.-diameter, 10% Enriched U-5 w/o Fs Alloy Specimens Versus Reactor Power for Various Fin Configurations.

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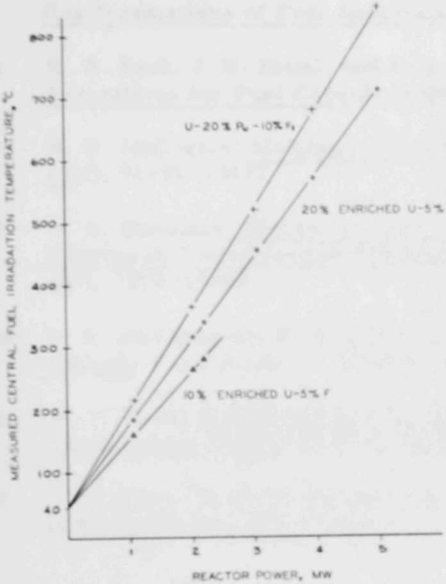

Figure 11

Irradiation Temperatures Versus Reactor Power for Three Fuel Materials Tested. The Capsule Vessel Was Made of Duplex Tubing Having 100 per cent Metal-to-Metal Contact.

Of a total of over twenty capsules irradiated in the CP-5 fuel thimbles to date, there has been no incident of release of fission products or contamination of the reactor coolant. Some of the capsules have been in the vertical thimbles for periods exceeding one year.

The capsules have been relatively simple to install and remove. This operation does not require more than 15 min and is accomplished with minimum hazard to operating personnel. Observations on the operating characteristics of the system have demonstrated that it can be operated unattended for extended periods of time. Other than periodic routine checks on the equipment, the only attention required is the placement of chart rolls, which is done once a month.

ACKNOWLEDGMENTS

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Figure 11

Irradiation Temperatures Versus Reactor Power of Three Fuel Materials Tested. The Capsule Vessel Was Made of Copper Tubing Having 100 per cent Metal-to-Metal Contact.

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