Argonne National Laboratory

EBR-II FUEL IRRADIATION FACILITIES

by

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and E. S. Sowa

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ABSTRACT

Two irradiation facilities, designed for installation within tubular fuel elements, and peripheral experimental thimbles in the CP-5 reactor core are described. Both units are cooled internally by natural convection of D_2O and feature an inherent variable temperature-control system which permits $\sim \pm$ 75-degree central metal temperature variation for a given heat-transfer rate. Heat-transfer rates ranging from 10 tkw (fuel) to 15 tkw (thimble) are possible. External cooling is provided by the reactor D_2O moderator.

Although designed primarily to simulate an operational environment for the evaluation of EBR-II prototype fuel elements, both facilities can be utilized for the irradiation of other fuel materials of interest, consistent with the internal geometry of each unit.

Complementary information includes thermal analyses and mock-up tests pertinent to the ultimate design.

I. INTRODUCTION

Advance knowledge of the physical and thermal characteristics of a conceptual fuel element is essential to the successful design of any reactor. The two facilities to be described were designed for installation in the CP-5 Research Reactor for the purpose of evaluating full-size fuel elements in an environment equivalent to the proposed operating conditions in the EBR-II.

Both units feature desirable characteristics of an ideal irradiation facility: (1) ease of loading; (2) simplicity of operation; (3) reliability; and (4) ease of unloading.

II. DESCRIPTION

A. General

Both facilities (hereafter identified as Unit No. 1 and Unit No. 2) feature variations of the same basic system dictated by their location in the CP-5 reactor. Each unit contains an encapsulated fuel specimen suspended by a stainless steel tube (1/4 in. OD x 0.035-in. wall) in a pressure vessel partially filled with heavy water. The heavy water serves as the capsule

coolant during irradiation and as shielding during unloading operations. Heavy water is used in lieu of light water to prevent contamination of the reactor heavy water moderator in the event of a leak in the pressure vessel.

Unit No. 1 (Fig. 1) is designed for installation in one of the experimental thimbles located at the periphery of the core. When installed, the pressure vessel is suspended in the heavy water moderator which provides the final heat sink for the heat generated by the fuel specimen during irradiation.

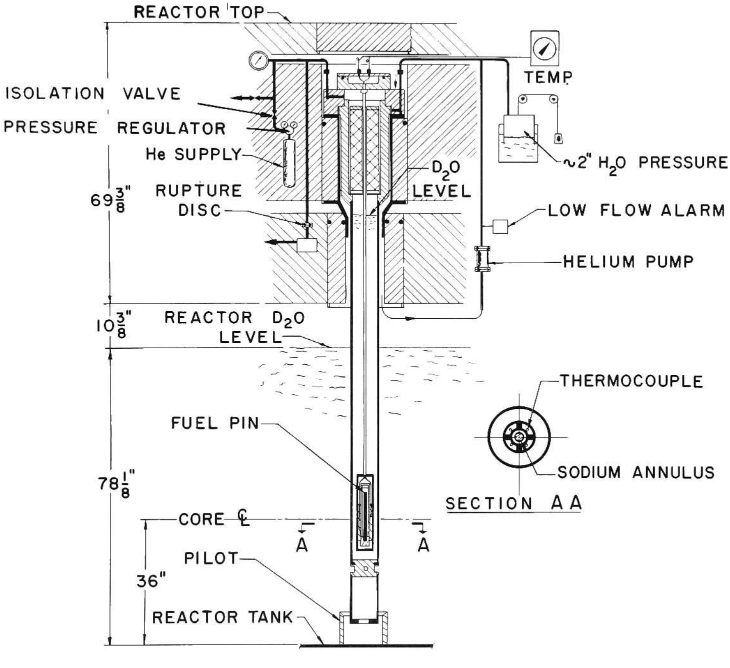


FIG. 1

EBR – II FUEL IRRADIATION FACILITY

(EXPERIMENTAL THIMBLE INSTALLATION)

Unit No. 2 (Fig. 2) is designed for installation in any one of the CP-5 aluminum tubular fuel-element thimbles. The heavy water moderator serves as the final heat sink, but an added resistance to heat flow is introduced by the annulus formed by the pressure vessel and the tubular fuel element thimble. The heavy water moderator enters the annulus through small perforations in the thimble and serves as the coolant of the pressure-vessel exterior. The mechanism of heat transfer in this annulus is not well understood; however, laboratory tests (see Appendix) indicate that the system is stable at power levels up to 10 kw. The aluminum thimble is cooled in the same manner as the reactor fuel tubes, namely, by forced circulation from a plenum at the bottom of the reactor tank.

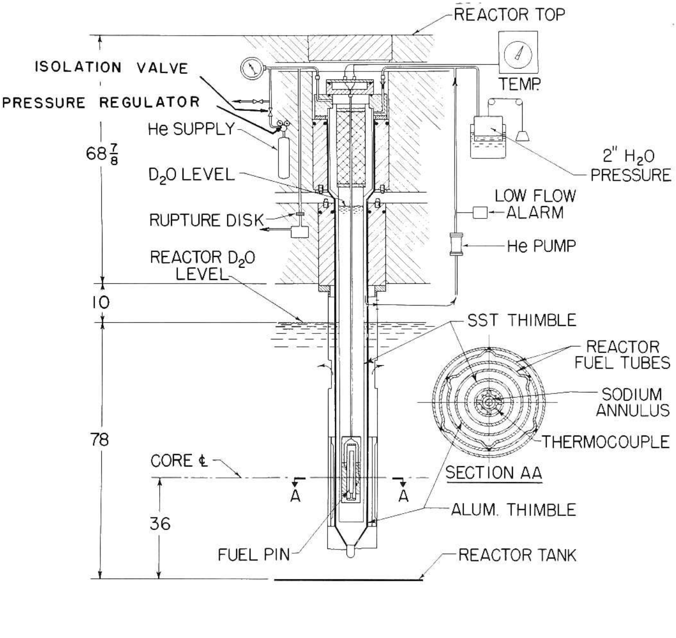


FIG. 2
EBR-II FUEL IRRADIATION FACILITY
(FUEL ELEMENT INSTALLATION)

The heavy water moderator is blanketed with helium which is maintained at a slightly positive pressure. Some dissociation of the moderator does occur; therefore, in order to prevent a build-up of deuterium and oxygen, the helium is circulated continuously through a catalytic recombiner. The test facility is equipped with a small diaphragm pump which circulated helium through the annulus formed by the irradiation facility and the reactor top shield to ensure against any build-up of dissociated gases in this region. A pressure switch on the discharge side of the pump actuates an alarm if the flow ceases.

B. Fuel Capsule

The function of the fuel capsule is to establish an environment for the fuel specimen similar to that which will exist in the EBR-II core. As shown in Fig. 3, the fuel specimen is thermally bonded with sodium to the inner surface of a stainless steel finned tube. The sodium is necessarily static, rather than flowing, although the sodium in the EBR-II will be moving. This is not considered a serious deviation. The four longitudinal fins are welded to cylindrical segments which, in turn, are welded to form a cylindrical capsule (Fig. 4). The intervening space contains air and thus presents a relatively high-resistance path for heat conduction. The path for heat flow is from the fuel pin, through the sodium bond and the radial fins, to the outer surface of the fuel capsule. The capsule is immersed in heavy water and local boiling occurs on the outer surface.

Temperatures along the length of the fuel specimen are monitored by thermocouples placed on the outer surface of the finned tube midway between the fin roots. The thermocouple leads extend upward through the tube which suspends the capsule from the top flange of the pressure vessel (Fig. 4).

C. Pressure Vessel

The pressure vessel for each unit is a stainless steel tube ($1\frac{1}{4}$ in. or $1\frac{1}{2}$ in. OD x 0.065-in. wall) welded to a modified thimble shielding plug and designed for 1100 psig at 600°F. Each vessel is partially filled with D_2O to a depth of 5 ft above the reactor core and is pressurized with helium from a high-pressure container (Figs. 1 and 2).

The operating range of pressure is 150 to 800 psig. Maximum operating pressure is set 300 psi below design pressure because the system is protected by a rupture disk. Rupture disks were selected over safety valves to improve the gas-tight integrity of the system. Manufacturers of rupture disks recommend setting the rupture pressure approximately 40% above the operating range to prevent premature disk failure.

In the event of a disk failure, the helium with some entrained steam discharges to a shielded container (designed to condense the steam) which exhausts to the reactor active vent system.

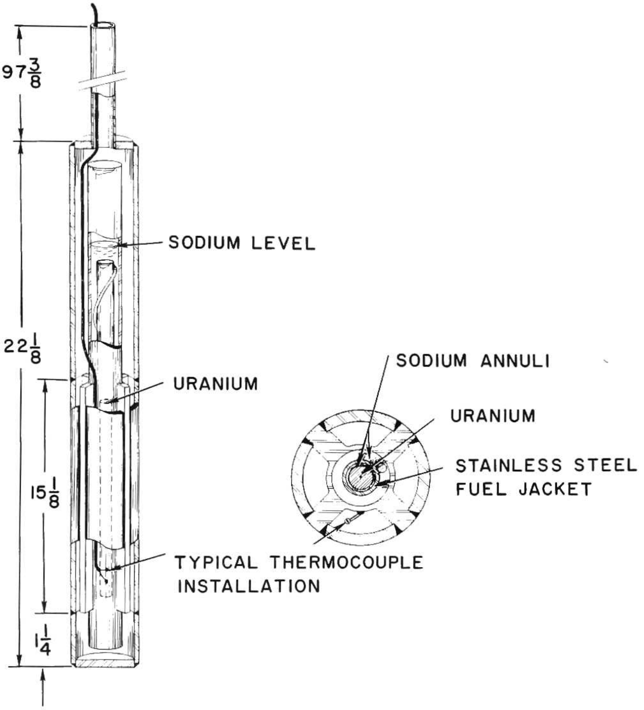


FIG 3
FUEL CAPSULE

The minimum pressure (150 psig) was established as a result of laboratory tests which disclosed that burnout of the capsule occurred at 50 psig and an operating power level of 10 kw. In practice, a safety factor of 100 psi has been added. Further, a minimum pressure must be maintained to ensure a pressure differential between the water in the vessel and the exterior coolant so that during operation the necessary temperature gradient can be established for outward flow of heat.

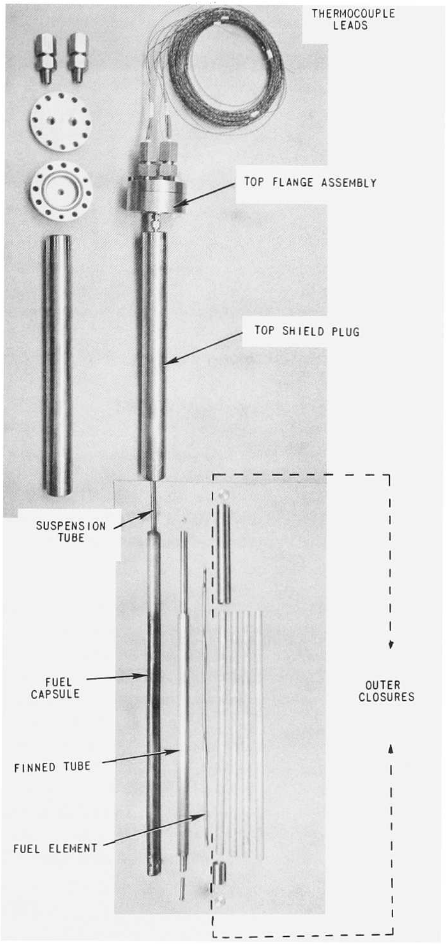


FIG. 4
IRRADIATION UNIT ASSEMBLY AND COMPONENTS

To prevent over-pressurization of the vessel in case of failure of the pressure regulator, the vessel is charged with helium during reactor operation and then isolated from the gas supply. Measures designed to ensure a gas-tight pressure system include (1) an all-welded vessel with a flanged closure sealed with rubber "O" rings; (2) flare-type fittings in the system tubing (copper: 1/4 in. OD x 0.065-in. wall); and (3) the use of rubber "O" rings for valve seats and stem packing.

D. Variable Temperature Control of Fuel Specimen

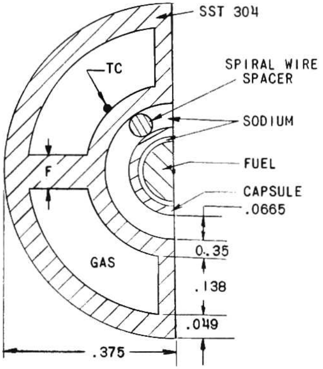
Variable temperature control of the fuel specimen is based on the principle that in a local boiling region the surface temperature of a heat source approximates the saturation temperature of the water over wide ranges of heat flux. The surface temperature can be controlled by varying the pressure and thus the saturation temperature of the water. Variation of pressure from 150 to 800 psig affords control of the central metal temperature over a range of ~150°F. If a fixed thermal resistance is then inserted between a constant heat source (in this case, the fuel specimen) and the surface in contact with the water, the temperature of the heat source can be raised and maintained at a given level.

The fuel enrichment and reactor flux determines the amount of heat generated in the fuel. The thermal resistance plus the local boiling at the fuel capsule surface regulate the outward flow of this heat. The combination of all four factors determines the temperature of the fuel during irradiation.

The generated heat and the temperature of the fuel are equivalent to values estimated for fuel elements during operation in the EBR-II. Since the temperature is controlled at the outer capsule surface, which is at a relatively low temperature (~450°F), a rather large temperature drop must be built into the capsule to raise the central metal temperature of the fuel specimen to the desired operating level (1100 to 1200°F). This is accomplished by sizing the fins to provide the necessary thermal resistance. The methods used to derive the fin thickness are described in the Appendix. The results are plotted in Fig. 5. With the known values of thermal resistance and the temperature difference Δt from the measuring point (fin root) to capsule surface, the heat generation (and thus the burnup) and central metal temperature may be calculated.

E. Instrumentation

The instrumentation consists of a multipoint temperature recorder equipped with a high-temperature scram, and a pressure recorder which features a "high" and a "low" scram.



METHOD OF CALCULATING MAXIMUM URANIUM TEMPERATURE

$$T_U = \left(\frac{R_C}{R_B}\right)\left(T_{CP} - T_W\right) + T_{CP}$$

where

T_U = maximum uranium temperature
T_{CP} = thermocouple temperature
T_W = outside surface temperature
R_C = resistance from curve (C)
R_B = resistance from curve (B)

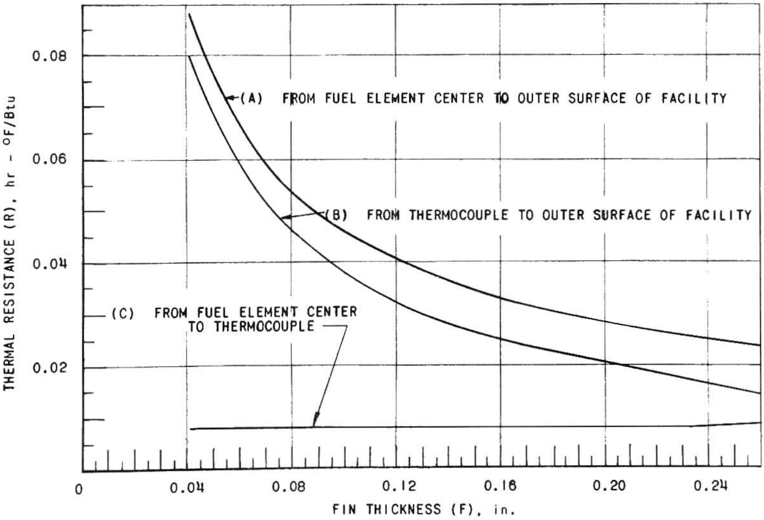


FIG. 5
THERMAL RESISTANCE VS FIN THICKNESS

III. LOADING PROCEDURE

The first step in preparing for a loading is to estimate the power generation (in Btu/hr), from reactor-flux data for the thimble to be used, and the enrichment of the fuel specimen. The operating temperature of the fuel-capsule surface is selected at a point midway between the temperature range corresponding to the maximum and minimum operating pressures. The desired operating fuel-element central metal temperature will give the required Δt by means of the equation

$$\Delta t = t_c - t_s \quad ,$$

where

t_c = fuel-element central metal temperature, °F

t_s = saturation steam temperature at vessel operating pressure, °F.

The thermal resistance (R) is calculated from the equation

$$R = \frac{\Delta t}{Q} \quad ,$$

where

Q = heat generation, Btu/hr.

The required fin thickness is determined from Curve A of Fig. 5. The finned tube is fabricated, the bottom plug is welded in place, and the thermocouples are attached to the fin roots. The side plates and bottom cap are welded to partially complete the outer tube.

The loading of the fuel specimen is performed in a dry box under an argon atmosphere. The tube is partially filled with a calculated volume of sodium and the fuel element is lowered to the bottom of the tube.

The unit is removed from the dry box and the top end plug is welded to complete the specimen assembly. The assembly is heated for 24 hr in an oven at 500°C to ensure complete bonding of the fuel specimen to the inner capsule wall. The outer closures are welded, and the suspension tube is welded to the fuel capsule. The shield plug and top flange assembly are mounted in position to complete the facility. The facility is installed in the pressure vessel located in the reactor, the thermocouple connections are made, and the facility is ready for operation.

IV. OPERATION

The pressure vessel is purged, and then pressurized with helium to the minimum operating pressure. After the reactor has been brought up to power, the pressure is raised slowly until the desired operating temperature is achieved. The pressure vessel is then isolated from the helium supply. The subsequent operation of the system is largely self-controlling. Some helium make-up may be required if there is a leakage in the pressure system.

V. OPERATING HISTORY

Two Units No. 1 and one Unit No. 2 have been installed and have operated in the CP-5 reactor for periods ranging up to 17 months. The maximum operating conditions achieved during this period have been (1) a specimen power level at 4.5 kw (thermal) and (2) a central metal temperature of 1200° F. Four fuel specimens have been irradiated, three of which are still in test. The performances of the three facilities have required only a minimum of supervision other than normal routine checks. The only difficulty encountered, which necessitated removal of one fuel capsule, was occasioned by a defect in the capsule weld closure which compromised the pressure-tight integrity of the unit. This incident served to emphasize the need for a more rigorous post-fabrication inspection. The current inspection sequence features an initial helium leak-detection test, followed by a 72-hr test in water at 1000 psig (saturation temperature), and a final helium leak-detection test.

VI. UNLOADING PROCEDURE

After reactor shutdown, the facility pressure vessel is depressurized and thoroughly purged to the reactor active vent system. The thermocouple leads are disconnected and the top flanges removed to separate the test assembly from the pressure vessel. The flange supporting the suspension tubing and the inner shield plug are removed. The heavy water in the pressure vessel provides adequate shielding during these operations.

The suspension tubing is attached with a cable to the winch in the coffin (Fig. 6), and the coffin is positioned above the pressure vessel. The cable and suspension tubing is wound around the drum, drawing the fuel capsule within the coffin. The bottom gate of the coffin is closed and the coffin removed to the high-level activity caves.

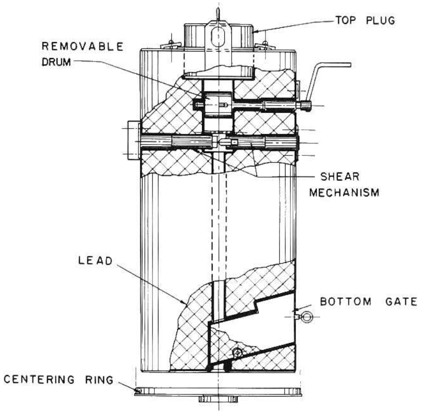


FIG. 6
REMOVAL COFFIN

Removal of the fuel capsule from the coffin can be accomplished either by (1) lifting the drum with the suspended capsule or (2) detaching the capsule from the tubing by operating the shear mechanism (anvil and chisel assembly) built in the coffin.

The fuel specimen is removed by cutting both the outer and inner tube above and below the fins with a tubing cutter.

VII. OTHER APPLICATIONS

Although designed primarily for the irradiation of prototype EBR-II fuel elements, both units can be adapted to provide an environment for the conduct of irradiation tests on other fuel materials pertinent to the advancement of reactor technology. Among others presently envisioned, the facilities could accommodate wafer-type elements and clusters, or rod-type or plate-type elements with dimensional tolerances consistent with the internal geometry of each unit.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the assistance rendered by W. R. Simmons during the conceptual design and mock-up experiments; R. W. Seidensticker for his thermal-stress analysis of the fuel capsule; W. H. McCorkle, in connection with installation and operation of the facility in the CP-5 reactor; and M. R. Gilbert for his suggestions with respect to the assembly of the fuel capsule and thermocouple installation.

Special credit is extended to F. J. Tebo who performed the electrical analogue analysis and the experiments confirming the thermal resistance in the fuel capsule, described in the appendix.

APPENDIX

DESIGN AND DEVELOPMENT

Mock-Up Tests

In the conceptual design of the facility, the pressure vessel was to be suspended inside one of the vertical experimental aluminum thimbles in the CP-5 reactor. Two thimble sizes existed at that time: a standard unit, 2 in. OD x $1\frac{3}{4}$ in. ID, and a special unit, 3 in. OD x $2\frac{3}{4}$ in. ID. Electrical mock-ups were built to determine the capability of each unit to remove heat. The heat-flow path studied extended from the capsule surface through the water system.

Each mock-up (Fig. 7) featured a stainless steel tube which simulated the outer tube of the fuel capsule and also served as a resistance heater. Four equally spaced copper wires were silver soldered axially on the inside wall, thus concentrating the heat generation (70% in the copper, 30% in the stainless steel), and thereby approximating the heat-flow conditions which exist in the reactor. The simulated fuel capsule was suspended in full-size stainless steel and aluminum thimbles which, in turn, were suspended in a temperature controlled water bath. The outer aluminum thimble was cooled by natural convection.

The test results showed that heat-removal rates as high as 15 kw (thermal) were practical with the special 3-in. thimble, and 10 kw (thermal) for the standard 2-in. thimble. The minimum operating pressure was determined by slowly reducing the pressure of the 2-in. unit while operating at 10 kw. Burnout of the capsule occurred at 50 psig.

After the mock-up tests were completed, two changes affecting these results were made: (1) the pressure vessel need not be isolated from the reactor heavy water if heavy water would be used as the coolant in the pressure vessel; and (2) a facility was to be designed for installation inside the (then new) CP-5 tubular-type fuel element.

The fact that isolation from the reactor was no longer a requirement indicated removal of the aluminum thimble, thus allowing the pressure vessel to be suspended directly in the heavy water of the reactor. Obviously the heat-removal capacity of the system is greatly increased; therefore, the 15-kw rating of the units in the experimental thimble locations is conservative.

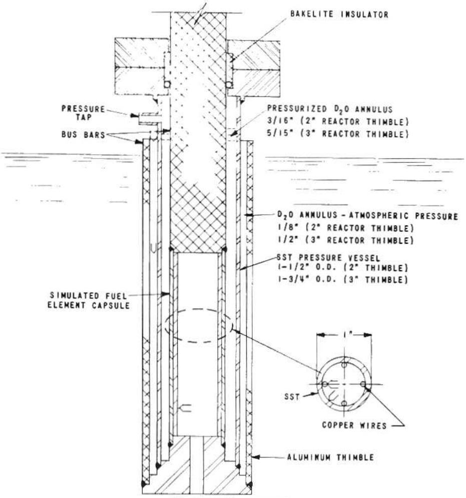


FIG. 7
HEAT TRANSFER MOCK-UP

While isolation from the reactor was not required in the tubular fuel-element facility, the aluminum thimble was retained for another reason. The reactor fuel element consists of two concentric tubes, containing enriched uranium which are cooled by forced convection from a plenum at the bottom of the reactor. The flow is orificed by a concentric inner tube (the aluminum thimble) and a concentric outer tube. Removal of the aluminum thimble would result in an increased annulus, thus reducing the coolant flow to the fuel tubes. The aluminum thimble could have been removed and replaced with a pressure vessel of the same diameter, but this would have required a heavier walled vessel which would have been detrimental to neutron economy. Therefore, the thimble was retained and the unit designed with the geometry used in the mock-up of the 2-in. thimble. The thimble is perforated with several small holes to allow the heavy water of the reactor to flood the annulus.

Thermal Resistance of Fuel Capsule

Radial thermal resistance through the fuel capsule was determined by an electrical analogue technique. A detailed description of the apparatus

and techniques has been reported by Simmons.* In brief, the technique utilizes the mathematical analogy between the flow of electrical and thermal energy in the solution of a complex heat-conduction problem by simulating the thermal system in terms of a more flexible electrical circuit.

In the present application, a representative cross section of the fuel capsule was mocked up with Teledeltos resistance paper, an electrically conducting medium consisting of a uniform dispersion of carbon black on paper backing. The mock-up, or model, was prepared in the exact configuration of the fuel capsule and on a scale 40 times larger, with the electrical conductivities of each material region in the same ratio to each other as the thermal conductivities in the fuel capsule This was accomplished by connecting several layers of Teledeltos paper in parallel in certain regions, or by using paper having different values of specific resistance. A standard resistance in the form of a single square of Teledeltos paper was connected in series with the model in the electrical circuit. Electric current from a 1.5-volt dry cell battery was passed through the fuel model and the standard resistance, causing a potential difference across each. The electrical current flow patterns in the model were the same as would be produced by the flow of heat energy in the fuel capsule. Potential differences across the model (ΔE_m) and the standard resistance (ΔE_s) were measured with a potentiometer.

The thermal resistances in the capsule were calculated with the use of the relation

$$R = \frac{1}{K} \frac{\Delta E_m}{\Delta E_s} \quad ,$$

where K is the equivalent thermal conductivity of the standard resistance. Essentially, the thermal resistance of the fuel capsule was determined by measuring the ratio of its resistance to that of the standard resistance simulating one of the fuel capsule materials with a thermal conductivity K. Values of the thermal resistance were obtained as a function of fin thickness (1) from the center of the fuel specimen to the outer surface of the capsule (Curve A, Fig. 5), and (2) from the thermocouple location to the outside surface of the capsule (Curve B, Fig. 5). The difference (Curve C, Fig. 5) was a nearly constant value for the range of fin thicknesses considered.

In addition to resistance determinations performed on the electrical analogue, a series of experimental measurements were made on three fuel

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*W. R. Simmons, "Electrical Geometrical Analogue Techniques for the Solution of Two-Directional Complex Heat Conduction Problems," ANL-5319 (September 1954).

capsules, each having a different value of fin thickness. This was done to determine the effects of welding and fabrication on thermal resistance, and to check the assumptions made for the analogue calculation.

A heat source was provided by passing steam through the center of the finned fuel capsule. The heat from the condensing steam, conducted radially through the finned capsule, was removed from the outside surface by cooling water flowing through a 1/16-in. annulus. Measurements were made of the coolant flow rate and temperature at the inlet and outlet of the annulus. Temperature measurements were also made by thermocouples at the fin root of the fuel capsule. These data were used to calculate heat balances and to determine the actual thermal resistances of the test specimens. The results agreed within 5% of the analogue data.