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 TO: R. J. Beaver
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PHASE I - FUEL SAMPLE IRRADIATION

Irradiation Request ORNL-MTR-35

C. F. Leitten and W. C. Thurber,

INTRODUCTION

A series of in-pile fuel sample irradiation experiments have been initiated to obtain radiation damage information on fuel material combinations applicable to Foreign Reactor Program Fuel Elements where U-235 enrichment is limited to 20%. The series of experiments will be divided into several phases, each being based on the materials combination employed. This report describes Phase I of the program which consists of determining the integrity and suitability of a 48 wt % U - 3 wt % Si - 49 wt % Al alloy as a fuel for Foreign Reactor Fuel Elements. The subsequent phases of this general program will be described in later reports.

DESIGN AND FABRICATION

This phase of the program entails irradiation of miniature fuel plates in the beryllium reflector of the MTR to burn-up values of 20, 40, 60 and 80% of the U-235 atoms. The fuel plates consist of a 20% enriched 48 wt % U - 3 wt % Si - 49 wt % Al alloy core, hermetically sealed within Al-clad 5050 frame and 1100 Al covers. The manufacturing stages for the miniature fuel plates are outlined below:

1. Miniature cores 0.725 in. x 0.555 in. x 0.229 in. were machined from a hot-rolled 48 wt % U - 3 wt % Si - Al alloy.
2. The cores were pressed into the Al-clad 5050 frame and hot-rolled at 575°C to a thickness of 0.180 in. in two equal passes.
3. The framed and pre-rolled cores were then enveloped with 1100 Al cover sheets, 0.122 in. thick and hot-rolled at 575°C, using 35% reductions per pass to a thickness of 0.065 in.
4. The hot-rolled plates were flux-annealed for one hr at 610°C and then cold-rolled to 0.060 in.
5. After a stress-relief anneal at 550° C for 45 min, the plates were roller leveled, marked and sheared and machined to 1 in. x 6 in. x 0.060 in.
6. Radiographs were then made and the plates were given a final blister-anneal for one hr at 610°C, prior to being assembled in "leaky rabbit" capsules.

The critical plate dimensions and fuel loadings for the uranium-silicon-aluminum alloy miniature fuel plates are listed in Table I.

FUEL PLATE TEMPERATURE CALCULATIONS

In an effort to evaluate the temperature conditions under irradiation existing in the miniature fuel plates, calculations were first made to estimate the coolant velocity at the plate surface.

The calculations which follow are based on the assumption that the capsule containing the fuel plate was inserted into the reflector tube with other rigs positioned so that a restricted flow of water resulted. The following sketch represents such a situation.

TABLE I

PERTINENT DATA ON URANIUM-SILICON-ALUMINUM ALLOY MINIATURE FUEL PLATES

Capsule and Plate No.	Finished Core Length (in.)	Finished Core Width (in.)	Finished Core Area (cm ²)	Core Weight (g)	U content of Core (g)	U-235 Content of Core* (g)	U-235 Surface Density (g/cm ²)	Finished Plate Length (in.)	Finished Plate Width (in.)	Finished Plate Thickness (in.)
OR-35-A-1	4.906	0.688	21.77	6.588	3.207	0.616	0.028	6.004	0.991	0.061
OR-35-A-2	4.938	0.688	21.91	6.519	3.173	0.609	0.028	6.003	0.991	0.061
OR-35-A-3	4.906	0.688	21.77	6.479	3.154	0.606	0.028	6.004	0.991	0.061
OR-35-A-4	4.938	0.688	21.91	6.619	3.222	0.619	0.028	6.004	0.991	0.061
OR-35-A-5	4.906	0.688	21.77	6.516	3.172	0.609	0.028	6.003	0.991	0.061
OR-35-A-6	4.969	0.688	22.05	6.510	3.169	0.608	0.028	6.000	0.991	0.060
OR-35-A-7	4.938	0.688	21.91	6.668	3.246	0.623	0.028	6.002	0.991	0.061
OR-35-A-8	4.969	0.688	22.05	6.514	3.171	0.609	0.028	6.002	0.991	0.060

* Based on an enrichment of 19.20% U-235.

As can be seen in this sketch, the water which flows by the obstruction has two channels in which to flow past the specimen-bearing capsule. These channels are indicated by v_1 and v_2 in the sketch.

Under these conditions the water velocity in each channel can be calculated on the basis of equal pressure drops in both channels and no interflow of water between the channels.

$$\Delta P_1 = f_1 \frac{1}{De_1} \frac{v_1^2}{2g} = \Delta P_2 = f_2 \frac{1}{De_2} \frac{v_2^2}{2g} \quad (1)$$

where:

- ΔP = pressure drop
- l = length of sample
- De = equivalent diameter
- v = velocity of fluid
- g = acceleration due to gravity

Equation (1) can be reduced under these assumptions to:

$$\frac{f_1 v_1^2}{De_1} = \frac{f_2 v_2^2}{De_2} \quad (2)$$

The equivalent diameter is defined as:

$$De = \frac{4A}{P}$$

where:

- A = cross sectional area of the channel
- P = total surface perimeter in the channel which is in contact with this coolant

From the sketch, the equivalent diameter of the outside channel can be determined as follows:

$$A_2 = \frac{\pi}{4} (D_2^2 - D_1^2)$$

$$P_2 = \pi D_2 + \pi D_1$$

$$De_2 = \frac{4\pi}{\pi(D_2 + D_1)} \left(\frac{D_2^2 - D_1^2}{4} \right) = D_2 - D_1 = 0.0104 \text{ ft}$$

In a similar manner the equivalent diameter for the inside channel can be determined.

$$De_1 = \frac{4A_1}{P_1} = 0.0459 \text{ ft}$$

Since the initial velocity of fluid entering the tube is approximately 30 ft/sec and assuming that this is the velocity of the water flowing past the obstruction, a first approximation of the water velocity in the total flow area can be made as follows:

$$v_1 A_1 = v_o A_o$$

where:

- A_1 = cross sectional area for water flow past the obstruction, (ft²)
- v_1 = velocity of coolant in this area, (30 ft/sec)
- v_o = velocity of coolant in entire flow area, (ft/sec)
- A_o = cross sectional area for entire flow, (ft)²

$$(30) \left(\frac{\pi}{4} \right) [(1.25)^2 - (1.125)^2] = v_o \left[\frac{\pi}{4} (1.25)^2 - (0.060)(0.996) \right]$$

where:

$$v_o = 6 \text{ ft/sec}$$

Therefore, assuming a flow of 6 ft/sec in both channels, the pressure drop for each can be calculated based on a water-coolant temperature of 140°F.

Using equation (1), the outside-channel pressure drop is:

$$\Delta P_2 = f_2 \frac{1}{De_2} \frac{v_2^2}{2g}$$

The friction factor in this equation can be obtained using a Friction Factor Chart, by first calculating the Reynolds number (N_{Re_2}) as follows and by assuming a normal roughness number for commercial tubing:

$$N_{Re_2} = \frac{v_2 De_2 \rho}{\mu} \quad (3)$$

where:

ρ = density of coolant (61.4 lb/ft³)

μ = viscosity of coolant (3.29×10^{-4} lb/sec-ft)

$$N_{Re_2} = \frac{(6)(0.0104)(61.4)}{0.49 \times 0.000672} = 1.16 \times 10^4$$

For a $N_{Re} = 1.16 \times 10^4$, $f = 0.035$ and using equation (1):

$$\Delta P_2 = \frac{0.035(0.5)(v_2^2)}{(0.0104)(2)(32.2)} = 0.0261 v_2^2$$

Following the same procedure for the pressure drop in the inside channel a $N_{Re} = 5.14 \times 10^4$ and a corresponding $f = 0.026$ were obtained. ΔP_1 was then similarly calculated, yielding

$$\Delta P_1 = \frac{0.026(0.5)(v_1^2)}{(0.0459)(2)(32.2)} = 0.0044 v_1^2$$

and since,

$$\Delta P_1 = \Delta P_2$$

it follows that

$$v_1 = 2.463 v_2 \quad (4)$$

Since all of the fluid must flow through these channels, the sum of the fluid flow in each channel must be equivalent to that entering past the obstruction:

$$A_1 v_1 + A_2 v_2 = A_1 v_i \quad (5)$$

Using equations (4) and (5), the following estimation of the velocity flow can be obtained:

$$(0.723)(2.463)v_2 + (0.233)v_2 = (30)(0.233)$$

where:

$$\begin{aligned} v_2 &= 3.5 \text{ ft/sec} \\ v_1 &= 8.6 \text{ ft/sec} \end{aligned}$$

Since both velocity values were initially based on a first approximation of 6 ft/sec, a more realistic value for the velocity can be obtained by repeating this procedure, using the newly determined velocity values. Making this calculation, velocity values for each channel are found to be:

$$\begin{aligned} v_2 &= 3.2 \text{ ft/sec} \\ v_1 &= 8.7 \text{ ft/sec} \end{aligned}$$

It can be seen that only slight changes were observed in the velocity values and these second approximated values are consequently, assumed to be conditions existing in the flow pattern.

Using a water-flow velocity of 8.7 ft/sec, the surface temperature of the fuel plate can be calculated by the following expression:

$$\frac{Q}{A_s} = h\Delta T \quad (6)$$

where:

- Q = heat generation
- A_s = total surface area of the core
- h = heat transfer coefficient of the coolant
- ΔT = is the temperature difference between the plate surface and the coolant

The heat transfer coefficient (h) is given by the following relation:

$$h \frac{De_1}{k_1} = 0.024 \left(\frac{v_1 De_1 \rho}{\mu} \right)^{0.8} \left(\frac{C_p \mu}{k} \right)^{0.4} \quad (7)$$

where:

- k = thermal conductivity of bulk coolant (0.377 BTU/hr-ft² F°/ft)
- ρ = density of coolant (61.4 lb/ft³)
- μ = viscosity of the coolant (3.29 x 10⁻⁴ lb/sec-ft)
- De₁ = equivalent diameter of the inside channel (0.046 ft)
- C_p = specific heat of the coolant (1.05 BTU/lb-F°)

Substitution of the various values for each constant again based on a coolant temperature of 140°F, results in a heat transfer coefficient

$$h = 1998 \text{ BTU/hr(ft)}^2 \text{ F}^\circ$$

The quantity of heat generated in the miniature plate can be found, using the following expression for Q:

$$Q = 0.45 \times 10^{-10} m\theta \quad (8)$$

where:

m = amount of U-235 present

θ = perturbed neutron flux

Assuming a perturbed flux of 5.6×10^{13} neut/cm²-sec on a sample containing 0.623 g of U-235, a value for Q can be obtained:

$$Q = 0.45 \times 10^{-10} m \theta$$

$$Q = 0.45 \times 10^{-10} (0.623) (5.6 \times 10^{13})$$

$$Q = 1.57 \times 10^3 \text{ watts, or}$$

$$Q = 1.57 \times 10^3 \times 3.413 = 5.36 \times 10^3 \text{ BTU/hr}$$

Assuming that the core is nominally 0.70 in. wide and 5.0 in. long, then the total surface area is:

$$A_S = \frac{2 \times (0.70)(5)}{144} = 0.049 \text{ ft}^2$$

It should be noted that the actual surface areas listed in Table I are slightly smaller.

Using equation (6), the surface temperature of the fuel plate is then:

$$\frac{Q}{A_S} = h(T_1 - T_2)$$

where:

T₁ = plate surface temperature (°F)

T₂ = temperature of the water coolant (140°F)

$$\frac{5.36 \times 10^3}{0.049} = 1998(T_1 - 140)$$

$$T_1 = \frac{110.25 \times 10^3 + 1998(140)}{1998}$$

$$T_1 = 195.2^\circ\text{F}$$

This temperature should not produce boiling of the water at the plate surface under the assumed coolant-velocity conditions.

The core temperature at the center-line thickness can be estimated by first calculating the core-clad interface temperature. This calculation assumes heat flow only in the perpendicular direction to the plate surface, from the core and can be found using the following expression:

$$\frac{Q}{A_S} = \frac{k}{L} = (T_3 - T_1)$$

where:

- k = conductivity of the cladding (118 BTU/hr-ft²-F°/ft)
- L = the clad thickness (0.0014 ft)
- T₃ = interface temperature (°F)
- T₁ = plate surface temperature (195.2°F)

$$110.25 \times 10^3 = \frac{118}{1.41 \times 10^{-3}} (T_3 - T_1) \quad (9)$$

$$T_3 = \frac{110.25 \times 10^3 + 83.69 \times 10^3(195.2)}{83.69 \times 10^3}$$

$$T_3 = 196.6^\circ\text{F}$$

Knowing the interface temperature and based on similar assumptions, the center-line-core temperature can be calculated with the following expression:

$$(T_4 - T_3) = g \frac{l^2}{2k} \quad (10)$$

where:

- T₄ = center-line-core temperature (°F)
- T₃ = interface core-clad temperature (196.6°F)
- g = heat generation per unit volume (BTU/ft³-hr)
- l = one-half the core thickness (1.08 x 10⁻³ft)
- k = conductivity of the core (BTU/hr-ft² - F°/ft)

$$g = \frac{Q}{V}$$

$$Q = 5.36 \times 10^3 \frac{\text{BTU}}{\text{hr}} \quad (\text{from equation (8)})$$

$$V = (\text{surface area of core}) \times (\text{core thickness})$$

$$V = \frac{0.70 \times 5 \times 0.026}{(12)^3} = 5.27 \times 10^{-5} \text{ft}^3$$

$$g = \frac{5.36 \times 10^3}{5.27 \times 10^{-5}} = 1.02 \times 10^8 \text{ BTU/ft}^3\text{hr}$$

The conductivity of the 48 wt % - 3 wt % Si - 49 wt % Al alloy core is approximately:

$$K = 1.25 \text{ watts/cm}^2 \text{ deg c/cm} \times \frac{1}{0.0173} = 72.25 \frac{\text{BTU}}{\text{hr-ft}^2\text{°F/ft}}$$

Therefore, using equation (10), the center-core temperature is:

$$T_4 = T_3 + g \frac{1^2}{2k}$$

$$T_4 = 196.6 + \frac{(1.02 \times 10^8)(1.08 \times 10^{-3})^2}{2(72.25)}$$

$$T_4 = 197.4^\circ\text{F}$$

TIME OF IRRADIATION

The estimated nvt values and time of irradiation to achieve 20%, 40%, 60% and 80% burn-up of U-235 are listed in Table II. These values are based on a minimum assumed unperturbed flux of 7×10^{13} neut/cm²-sec. A sample calculation of the values indicated in Table II for the 20% burn-up samples as follows:

The estimated nvt required for the 20% burn-up of U-235 atoms in samples OR-35-A-1 and 2 is given by:

TABLE II

ESTIMATED NVT AND TIME OF IRRADIATION DATA

Sample No.	Minimum Unperturbed Flux(neut/cm ² -sec)	Desired U-235 Burn-up	Estimated nvt	Estimated Exposure Time (days)
OR-35-A-1	7×10^{13}	20%	4.99×10^{20}	118
OR-35-A-2	7×10^{13}	20%	4.99×10^{20}	118
OR-35-A-3	7×10^{13}	40%	11.41×10^{20}	269.7
OR-35-A-4	7×10^{13}	40%	11.41×10^{20}	269.7
OR-35-A-5	7×10^{13}	60%	20.49×10^{20}	484.4
OR-35-A-6	7×10^{13}	60%	20.49×10^{20}	484.4
OR-35-A-7	7×10^{13}	80%	35.98×10^{20}	850.6
OR-35-A-8	7×10^{13}	80%	35.98×10^{20}	850.6

$$\frac{dN}{dt} = -N\sigma\phi \quad (11)$$

where:

- N = number of U-235 atoms per unit volume (cm^{-3})
- σ = average absorption cross section of U-235 (cm^2)
- ϕ = unperturbed flux ($\text{neut}/\text{cm}^2\text{-sec}$)
- α = reciprocal of the disadvantage factor (0.80)
- t = time (sec)

Solving equation (11)

$$N(t) = N_0 e^{-\alpha\sigma\phi t}$$

or Burn-up =

$$1 - \frac{N(t)}{N_0} = 1 - e^{-\alpha\sigma\phi t}$$

Assuming an average reflector temperature of 140°F, the average absorption cross section for U-235 is:

$$\bar{\sigma}_a = 596 \times 10^{-24} \sqrt{\frac{293}{333}} = 559 \times 10^{-24} \text{ cm}^2$$

Then solving the equation for the total integrated flux, the required nvt for 20% Burn-up is:

$$t = \frac{\ln N}{-\alpha\sigma\phi}$$

$$t = \frac{\ln(0.8)}{-(0.8)(7 \times 10^{13})(559 \times 10^{-24})}$$

$$t = 7.13 \times 10^6 \text{ sec}$$

$$\text{nvt} = 7 \times 10^{13} \times 7.13 \times 10^6 \text{ sec} = 4.99 \times 10^{20}$$

Assuming 70% operation and an unperturbed flux of 7×10^{13} neut/cm²-sec in the reflector, the estimated irradiation time is:

$$\frac{4.99 \times 10^{20}}{(7 \times 10^{13})(3600)(24)(0.70)} = \frac{4.99 \times 10^{20}}{4.23 \times 10^{18}} = 118 \text{ days}$$

The heat generation in the fuel sample appears in the Fuel Plate Temperature Calculations Section of this report and can be determined, using equation (8). The value obtained for a fuel sample containing 0.623 g of U-235 and in a perturbed flux of 5.6×10^{13} neut/cm²-sec is:

$$Q = 1.57 \times 10^3 \text{ watts}$$

The heat output in watts/in. can be obtained as follows:

$$\frac{1.57 \times 10^3}{5 \text{ (in.)}} \text{ watts} = 3.14 \times 10^2 \text{ watts/in.}$$

The thermal flux can be calculated by the ratio of $\frac{Q}{A_S}$ which appears in equation (6).

where:

Q = heat generated (BTU/hr)

A_S = total surface area of core (ft)²

$$\frac{Q}{A_S} = \frac{(1.57 \times 10^3)(3.413)(144)}{(2 \times 0.7 \times 5)} = 110.25 \times 10^3 \frac{\text{BTU}}{\text{ft}^2\text{-hr}}$$

The thermal calculations presented in this report are based on assumptions which should yield the maximum heat generation and maximum temperature conditions existing in the miniature fuel plates during irradiation. In the event that reflector positions are available with unperturbed flux values greater than 7×10^{13} neut/cm²-sec, such positions would be more desirable in order to decrease the time of exposure.