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PROPOSAL FOR IRRADIATION OF URANIUM SWELLING
BEHAVIOR CAPSULES

J. W. Weber

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PROPOSAL FOR IRRADIATION OF URANIUM SWELLING BEHAVIOR CAPSULES

J. W. Weber

I. INTRODUCTION

The swelling behavior of unalloyed clad uranium operating with a cladding surface temperature of 250-350 C and fuel temperatures from 450-750 C is of importance for Hanford's fuel element development work. To obtain information on the effect of cladding restraint, exposure, and the above temperatures, on uranium swelling rates, a series of experiments is proposed for irradiation in Hanford reactors. The experimental assemblies consist of uranium fuel rods supported concentrically in an aluminum capsule. Surrounding the fuel rod is an annulus of liquid NaK to serve as a heat transfer agent.

II. OBJECTIVE

This irradiation is proposed to measure the swelling behavior of unalloyed uranium fuel rods clad in Zr-2 by coextrusion process. By suitable manipulation of capsule design parameters and proper selection of irradiation conditions, temperatures in the ranges suggested above will be obtained. Uranium exposures are to be from 1500 to 5000 MWD/T.

III. TEST DESIGN

The design of this test requires the irradiation of six capsules per process tube, the number of tubes required being dependent upon the number of different restraint, temperature and exposure conditions to be investigated. Each set of conditions will be triplicated. The six capsules are to be centrally located in the process tube to take advantage of the maximum flux and the minimum flux change front to rear. No other fuel or poison elements are to be charged in these tubes during this irradiation.

Because uranium swelling behavior is temperature sensitive, it is very important in this test to know the uranium temperatures. Design and space limitations of the capsules make it feasible to measure the uranium temperature in only the downstream capsule. This temperature together with the average adjacent tube power and weasel measurements of the front to rear flux distribution will make it possible to calculate the temperature distributions in the five remaining upstream capsules.

Initially four process tubes with six capsules each will be required to cover the test conditions of immediate interest, however additional tests will be desired eventually which will require up to eight more process tubes. The proposed tube loadings are shown in Table I with the capsule at the top to be thermocoupled. The sequence of capsules except the thermocoupled one is not necessarily that which would be finally charged. The

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coding of the samples is indicated in Table II with the cladding thicknesses, temperatures desired and calculated, and exposures.

TABLE I

PROPOSED TUBE LOADINGS OF SWELLING CAPSULES

Tube Sample	1	2	3	4
A231	A231	A233	A323	B231
A232	A232	A331	A222	B232
A333	A333	A332	A221	B233
A211	A211	A213	A223	B331
A212	A212	A311	A321	B332
A313	A313	A312	A322	B333

TABLE II

Sample	Cladding Inches	Power Req'd. Kw/ft.	Temperatures - °C				Exposure MWD/T
			Axial		Cladding Surface		
			Desired	Calculated	Desired	Calculated	
A211	0.020	24	250	264	500	514	1500
A212	0.020	24	250	264	500	514	1500
A213	0.020	24	250	264	500	514	1500
A221	0.020	33	250	273	600	603	1500
A222	0.020	33	250	273	600	603	1500
A223	0.020	33	250	273	600	603	1500
A231	0.020	24	350	358	600	608	1500
A232	0.020	24	350	358	600	608	1500
A233	0.020	24	350	358	600	608	1500
A311	0.030	24	250	249	500	526	1500
A312	0.030	24	250	249	500	526	1500
A313	0.030	24	250	249	500	526	1500
A321	0.030	33	250	257	600	624	1500
A322	0.030	33	250	257	600	624	1500
A323	0.030	33	250	257	600	624	1500
A331	0.030	24	350	365	600	632	1500
A332	0.030	24	350	365	600	632	1500
A333	0.030	24	350	365	600	632	1500
B231	0.020	24	350	358	600	608	3000
B232	0.020	24	350	358	600	608	3000
B233	0.020	24	350	358	600	608	3000
B331	0.030	24	350	365	600	632	3000
B332	0.030	24	350	365	600	632	3000
B333	0.030	24	350	365	600	632	3000

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IV. DESCRIPTION OF IRRADIATION ASSEMBLIES

A. Sizes and Geometry

The basis for the capsule design is explained in HW-56132.

The assembled capsules are shown in Figures 1 and 2 and the detail dimensions are on the attached prints H-3-5960 and SK-3-7936. The variable dimensions of D1 and S in H-3-5960 and D2 on SK-3-7936, that are used in each capsule, are given in Table III.

In six of the capsules it is necessary to insert a Zr-2 thermal shield to increase the temperature drop at the capsule. Details at these shields are shown in Figure 3, and the dimensions are given in Table III.

A perf train will run from the thermocouple capsule extension to the rear face of the reactor to provide support from the thermocouple lead and to locate the capsules at the desired position in the process tube. It is necessary to orient the capsule rotationally in the process to keep the expansion chambers in the up position at all times.

TABLE III

<u>Sample</u>	<u>D1</u>	<u>A</u>	<u>Zr-2 Sleeve</u>		<u>D2</u>
	inches	inches	ID-inches	OD-inches	inches
A211	0.864	0.168			0.864
A212	0.864	0.168			0.864
A213	0.864	0.168			0.864
A221	0.763	0.218			0.763
A222	0.763	0.218			0.763
A223	0.763	0.218			0.763
A231	0.920	0.140	0.710	0.860	0.710
A232	0.920	0.140	0.710	0.860	0.710
A233	0.920	0.140	0.710	0.860	0.710
A311	0.875	0.162			0.875
A312	0.875	0.162			0.875
A313	0.875	0.162			0.875
A321	0.772	0.214			0.772
A322	0.772	0.214			0.772
A323	0.772	0.214			0.772
A331	0.950	0.125	0.710	0.880	0.710
A332	0.950	0.125	0.710	0.880	0.710
A333	0.950	0.125	0.710	0.880	0.710
B231	0.920	0.140	0.710	0.860	0.710
B232	0.920	0.140	0.710	0.860	0.710
B233	0.920	0.140	0.710	0.860	0.710
B331	0.950	0.125	0.710	0.880	0.710
B332	0.950	0.125	0.710	0.880	0.710
B333	0.950	0.125	0.710	0.880	0.710

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12/23/58**B. Materials**

The capsule body is machined from rod stock of ALCOA C-64 aluminum alloy. The end plugs, capsule extension and hex heads is made from aluminum alloy 1100. The end caps are machined from standard Hanford end caps.

The fuel rod is 1.6% enriched uranium coextruded with Zr-2 cladding. Separating the fuel rod and capsule body is an annulus of liquid NaK.

C. Fabrication

The fuel rod end cap and thermocouple thimble, both Zr-2 are welded together by the electron gun welder, as are the capsule end plugs and body. The thermocouple is inserted into the capsule, sealed, and He leak checked after the fuel rod is loaded and the end plug welded on to the body. Both types of capsules are filled in a He atmosphere glove box, through the threaded hole in the end plug which is then sealed, welded, and He leak checked before the end caps are welded on.

D. Inspection and Proof Testing

Inspections for weld and swage-lok seal leaks are made as needed at various stages of the assembly.

The capsules will be hot water autoclaved after complete assembly.

V. EXPECTED PERFORMANCE**A. Mechanical Behavior**

To prevent distortion of the capsule by internal pressure, developed from uranium swelling and/or thermal expansion of the NaK, an expansion chamber is provided in each capsule. The bases for the design and dimensions of this expansion chamber are given in HW-56132.

B. Failure Behavior

There has been no experience on the in-reactor failure behavior of these capsules, however, tests were run on 8 NaK filled capsules that were deliberately failed in 98 C water in the 314 Building flow tubes⁽¹⁾. After running for two hours, the NaK had been completely flushed from the capsules. There was no distortion and no serious corrosion of the inside or outside of the capsules. Once the NaK is gone from the capsule, the fuel will become hot and must be discharged from the reactor. Failure of the capsule can be detected by the presence of Na₂H in the process water outlet.

C. Charge and Discharge of Capsules

(1) Weber, J. W., "Results of NaK Capsule Failures in Hot Water Flow Tube." HW-56588, 6-30-58.

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The decision on whether to charge the five non-thermocouple capsules from the front or rear face will be made after the tubes have been selected. An initial charging⁽²⁾ of one of the thermocouple capsules was made in DR reactor from the rear face and found to work very satisfactorily.

Discharging should present no further difficulties than the discharge of any other lead type experiment.

XI. OPERATIONAL LIMITATIONS

A. Temperature

Large temperature transients were observed at reactor startups during the irradiation of an initial swelling capsule in DR reactor. It is expected that transients will also be observed during startups with this irradiation. The thermocouple temperatures should be watched during the reactor startup and the increase to full power. If during startup the measured temperature exceeds the calculated temperature by more than 250 C and remains at this high value long enough to determine that it is not a short term transient then the tube should be discharged. If, over a period of 1 to 2 days, the measured temperature steadily increases by more than 150 C over its maximum calculated value the tube should be discharged.

The small amount of heat generating material should raise the water temperature 10-15 C.

VII. IRRADIATION CONDITIONS

A. Desired Conditions for Test

1. Power generation desired in fuel - See Table II.
2. Tube power required:

3 tubes at 700 kw/tube

1 tube at 960 kw/tube

See Appendix A for calculation of tube powers.

3. Time of Exposure:

Tube 1	69	Days
2	68	Days
3	50	Days
4	136	Days

(2) Kratzer, W. K., PT IP-200-A "Temperature Measurement of Uranium Swelling Capsule," HW-57109, 7-11-58

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4. Temperatures - °C

<u>Sample</u>	<u>Uranium Axial</u>	<u>Cladding Surface</u>	<u>Capsule Surface</u>	<u>Local Coolant</u>
A21(1-3)	514	264	50	15
A22(1-3)	603	273	63	15
A23(1-3)	608	358	50	15
A31(1-3)	526	249	50	15
A32(1-3)	624	257	63	15
A33(1-3)	632	365	50	15
B23(1-3)	608	358	50	15
B33(1-3)	632	365	50	15

B. Acceptable Deviations

The success of these tests is dependent upon the ability to obtain the desired temperatures and maintain them during the irradiation. In each tube there are capsules with uranium operating in the high temperature range. It is important the they do not exceed the α - β transformation temperatures. These are the critical capsules in each tube and will dictate the acceptable deviations.

<u>Tube</u>	<u>Acceptable Deviations in Specific Power</u>
1	+4% - 8%
2	+4% - 8%
3	+3.5% - 3%
4	+4% - 8%

This corresponds to a tube power deviations of

<u>Tube</u>	
1	+4% - 8%
2	+4% - 8%
3	+3% - 3%
4	+4% - 8%

A tube power increase of 50% could cause the following maximum temperatures:

<u>Tube</u>	<u>Temperature -°C</u>
1	926
2	926
3	908
4	926

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VIII. INSTRUMENTATION

Each process tube will have a thermocouple in the downstream capsule to measure the uranium core temperature. The leads will be removed through the rear face.

IX. REACTOR DATA REQUIRED

At eight-hour intervals and before any drastic change is expected in the reactor operations, the following information is desired:

Date, time, reactor power level, water inlet temperature and

- a. Outlet temperature
- b. Panellit dial and base
- c. Header dial and base

from each adjacent tube surrounding the four tubes in which the capsules are charged.

X. DISPOSITION OF CAPSULE

After discharge, the capsules are to be stored for a sufficient decay period. They will then be removed to HAP0 Radiometallurgy Facility for opening and examination of the fuel rods.

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Fuel Element Design Operation

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APPENDIX A

TUBE POWER CALCULATION

BASIS FOR CALCULATION

If it is assumed that the flux peak in a given tube could oscillate at least the length of the capsule train, then it must be assumed that the capsule operating with the maximum uranium axial temperature T_a would be at times subjected to this peak. The average required tube power must then be based on this assumption, that is, that the maximum T_a capsule would be at some time in the location of the maximum slug factor.

The maximum slug factor can only be correctly determined by flux traverse data on that particular tube or adjacent tubes. Assume that the flux distribution is similar to that found from the traverse data of PT-IP-200A. This corresponds approximately to a flux distribution curve of $\sin N + 0.20 \sin 2N$ as found in HW 56522 "Slug Factors for Various Flux Distributions". The maximum slug factor for this curve is 0.045.

An equation relating ΔT of the capsule and adjacent tube power is:

$$\text{Avg. Adj. Tube Power} = \frac{\Delta T_c}{\left(\frac{\Delta T_c}{T_c}\right) (f) (r) (Nu. \text{ Adj. Fac} \text{ Slug/ft})}$$

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where:

ΔT_c - Temperature drop in capsule
 $T_a - T_{water}$

f - slug factor 0.045

r - Ratio of power in capsule to power
in adjacent slug
0.569 Non thermocouple capsule
0.552 Thermocouple capsule

$\frac{\Delta T_c}{Q_c}$ - $^{\circ}C$ temperature drop in capsule
per KW/ft of power in capsule

TUBE 1

The capsule with the maximum T_a is A333

$$\Delta T_c = 617^{\circ}C$$

$$Q_c = 24 \frac{\text{KW}}{\text{ft}}$$

$$r = 0.569$$

$$\frac{\Delta T_c}{Q_c} = 25.71 \frac{^{\circ}C}{\frac{\text{KW}}{\text{ft}}}$$

$$\begin{aligned} \text{Tube power} &= \frac{617}{(25.71)(0.045)(0.569)(1.34)} \\ &= 700 \frac{\text{KW}}{\text{tube}} \end{aligned}$$

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TUBE 2

The capsules with the maximum T_a is A 331 and A 332 which have the same temperature and power conditions as A 333.

The tube power is therefore the same as tube 1 - $700 \frac{\text{KW}}{\text{tube}}$

TUBE 3

Capsules A 321, A 322, A 333 have the maximum T_a .

$$\Delta T_c = 607^\circ\text{C}$$

$$Q_c = 33 \frac{\text{KW}}{\text{ft}}$$

$$r = 0.569$$

$$\frac{\Delta T_c}{Q_c} = 18.39 \frac{^\circ\text{C}}{\frac{\text{KW}}{\text{ft}}}$$

$$\begin{aligned}\text{Tube power} &= \frac{607}{(18.39)(0.045)(0.569)(1.34)} \\ &= 960 \frac{\text{KW}}{\text{tube}}\end{aligned}$$

Calculation of power requirement for 24 and 34 sample shows tube power = $962 \frac{\text{KW}}{\text{tube}}$.

TUBE 4

Capsules in Tube 4 have the same power and temperature conditions as the capsules in tubes 1 and 2.

$$\text{Tube power} = 700 \frac{\text{KW}}{\text{ft}}$$

Field Bond Line

Weld (Electron Gun)

Ring Side Ring

FIGURE 1

ASSEMBLED CATHODE COATING WITH ANGLE CAUSE

Coating

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FIGURE
ASSEMBLED SWEP

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Annulus

fuel Rod

Helium Filled Expansion Chamber

End Caps

E 2

LING CAPSULE

NONE

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APPENDIX B

HEAT TRANSFER CALCULATIONS

ASSUMPTIONS

Water Temperature 15°C
Water Flow 30 GPM

FILM COEFFICIENT

$$\frac{h D_e}{k} = 0.027 \left(\frac{\rho V D_e}{\mu} \right)^{0.8} \left(\frac{C_p \mu}{k} \right)^{0.33}$$

$$k = 0.33 \frac{\text{Btu}}{\text{hr} \cdot \text{ft} \cdot ^\circ\text{F}}$$

$$\rho = 62.4 \frac{\text{lb}}{\text{ft}^3}$$

$$\mu = 3.24 \frac{\text{lb}}{\text{m} \cdot \text{ft}}$$

$$C_p = 1 \frac{\text{Btu}}{\text{lb} \cdot ^\circ\text{F}}$$

$$D_e = 0.0167 \text{ ft}$$

$$V = 71200 \frac{\text{ft}}{\text{hr}}$$

$$\frac{h (0.0167)}{0.33} = 0.027 \left[\frac{(62.4)(71200)(0.0167)}{3.24} \right]^{0.8} \left[\frac{(1)(3.24)}{0.33} \right]^{0.33}$$

$$h = 0.027 (22900)^{0.8} (9.818)^{0.33} (19.76)$$

$$= (0.027)(3075)(2.123)(19.76)$$

$$= 3485 \frac{\text{Btu}}{\text{hr} \cdot \text{ft}^2 \cdot ^\circ\text{F}}$$

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TEMPERATURE DROPS

Thermal Conductivities

Uranium K_1

$\frac{\text{Btu}}{\text{hr} \cdot \text{ft} \cdot ^\circ\text{F}}$

20.1 (500°C)

21.3 (600°C)

Zr-2 K_2

8.2

Na K K_3

14

Aluminum K_4

127

Thermal Coefficients

Zr-2 and uranium Bond h_1

$\frac{\text{Btu}}{\text{hr} \cdot \text{ft}^2 \cdot ^\circ\text{F}}$

20,000

Water film h_2

3,485

Dimensional Nomenclature

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Sample A21

$$\Delta T_{rod} = \Delta T_{uranium} + \Delta T_{zr-v bond} + \Delta T_{zr cladding}$$

$$\Delta T_v = \frac{Q}{4\pi k_1}$$

$$Q = 24 \frac{ft}{ft} \quad k_1 = 20.1 \frac{m-ft-0F}{Btu}$$

$$= \frac{4\pi(20.1)(1.8)}{(24)(3413)}$$

$$= 180^\circ C$$

$$\Delta T_{zr-v} = \frac{h_1 A}{Q}$$

$$= \frac{(30,000)\pi(0.570)(1.8)}{(24)(3413)(12)}$$

$$= 10^\circ C$$

$$\Delta T_{zr} = \frac{Q}{2\pi k_2} \ln \frac{d_1}{d_2}$$

$$= \frac{2\pi(8.2)(1.8)}{(24)(3413)(0.0677)}$$

$$= 0.0677$$

$$\ln \frac{d_1}{d_2} = \ln \frac{0.610}{0.570}$$

$$= 60^\circ C$$

$$\Delta T_{fuel rod} = 250^\circ C$$

$\Delta T_{Nek} \text{ Annulus}$

$$\Delta T_{Nek} = \frac{Q}{2\pi k_3} \ln \frac{d_2}{d_3}$$

$$= \frac{2\pi(14)(1.8)}{(24)(3413)(0.3549)}$$

$$= 184^\circ C$$

$$\ln \frac{d_2}{d_3} = \ln \frac{0.864}{0.610} = 0.3549$$

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DT Aluminium Body

$$\begin{aligned}\Delta T_{Al} &= \frac{Q}{2\pi k g} \ln \frac{d_o}{d_i} \\ &= \frac{(24)(3413)(0.518)}{2\pi (127)(1.8)} \\ &= 30^\circ\text{C}\end{aligned}$$

$$\begin{aligned}\ln \frac{d_o}{d_i} &= \ln \frac{1.44}{0.864} \\ &= 0.518\end{aligned}$$

DT Water Film

$$\begin{aligned}\Delta T_w &= \frac{Q}{h_c A} = \frac{(24)(3413)(12)}{(3485)(\pi)(1.44)(1.8)} \\ &= 35^\circ\text{C}\end{aligned}$$

Temperature Capsule Surface

$$\begin{aligned}T_c &= T_w + \Delta T_w \\ &= 15 + 35 = 50^\circ\text{C}\end{aligned}$$

Temperature Cladding Surface

$$\begin{aligned}T_s &= T_w + \Delta T_w + \Delta T_{Al} + \Delta T_{Nuc} \\ &= 15 + 35 + 30 + 184 \\ &= 264^\circ\text{C}\end{aligned}$$

Temperature Uranium Axis

$$\begin{aligned}T_u &= T_s + \Delta T_{rod} \\ &= 264 + 250 \\ &= 514^\circ\text{C}\end{aligned}$$

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Sample A33

$$\Delta T_{rod} = \Delta T_0 + \Delta T_{0-2r} + \Delta T_{2r}$$

$$Q = 24 \frac{\text{kw}}{\text{ft}}$$

$$k_1 = 21.3 \frac{\text{Btu}}{\text{m-ft} \cdot ^\circ\text{F}}$$

$$\begin{aligned}\Delta T_0 &= \frac{Q}{4\pi k_1} \\ &= \frac{(24)(3413)}{4\pi(21.3)(1.8)} \\ &= 170^\circ\text{C}\end{aligned}$$

$$\begin{aligned}\Delta T_{0-2r} &= \frac{Q}{h \cdot A} \\ &= 10^\circ\text{C}\end{aligned}$$

$$\begin{aligned}\Delta T_{2r} &= \frac{Q}{2\pi k_2} \ln \frac{d_2}{d_1} \\ &= \frac{(24)(3413)(0.0988)}{2\pi(8.2)(1.8)} \\ &= 87^\circ\text{C}\end{aligned}$$

$$\begin{aligned}\ln \frac{d_2}{d_1} &= \ln \frac{0.630}{0.570} \\ &= 0.0998\end{aligned}$$

$$\Delta T_{\text{fuel rod}} = 267^\circ\text{C}$$

$\Delta T_{\text{First Nak Annulus}}$

$$\begin{aligned}\Delta T_{\text{Nak1}} &= \frac{Q}{2\pi k_3} \ln \frac{d_3}{d_2} \\ &= \frac{(24)(3413)(0.1193)}{2\pi(14)(1.8)} \\ &= 62^\circ\text{C}\end{aligned}$$

$$\begin{aligned}\ln \frac{d_3}{d_2} &= \ln \frac{0.710}{0.620} \\ &= 0.1193\end{aligned}$$

$\Delta T_{2r-2} \text{ Sleeve}$

$$\begin{aligned}\Delta T_{2r-2} &= \frac{Q}{2\pi k_2} \ln \frac{d_4}{d_3} \\ &= \frac{(24)(3413)(0.2142)}{2\pi(8.2)(1.8)} \\ &= 129^\circ\text{C}\end{aligned}$$

$$\begin{aligned}\ln \frac{d_4}{d_3} &= \ln \frac{0.880}{0.710} \\ &= 0.2142\end{aligned}$$

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DT Second NaK Annulus

$$\begin{aligned}\Delta T_{NaK2} &= \frac{Q}{2\pi k_s} \ln \frac{d_3}{d_4} \\ &= \frac{(24)(3413)(0.0767)}{2\pi(14)(1.8)} \\ &= 40^\circ\text{C}\end{aligned}$$

$$\begin{aligned}\ln \frac{d_4}{d_3} &= \ln \frac{0.930}{0.880} \\ &= 0.0767\end{aligned}$$

DT Aluminum Body

$$\begin{aligned}\Delta T_{Al} &= \frac{Q}{2\pi k_4} \ln \frac{d_6}{d_5} \\ &= \frac{(24)(3413)(0.4158)}{2\pi(127)(1.8)} \\ &= 24^\circ\text{C}\end{aligned}$$

$$\begin{aligned}\ln \frac{d_6}{d_5} &= \ln \frac{1.44}{0.950} \\ &= 0.4158\end{aligned}$$

DT Water Film

$$\begin{aligned}\Delta T_w &= \frac{Q}{h_2 A} \\ &= \frac{(24)(3413)(12)}{(3483)(\pi)(0.44)(1.8)} \\ &= 35^\circ\text{C}\end{aligned}$$

Temperature Capsule Surface

$$T_c = 50^\circ\text{C}$$

Temperature Cladding Surface

$$\begin{aligned}T_s &= T_w + \Delta T_w + \Delta T_{Al} + \Delta T_{NaK2} + \Delta T_{2v} + \Delta T_{NaK1} \\ &= 15 + 35 + 24 + 40 + 189 + 62 \\ &= 365^\circ\text{C}\end{aligned}$$

Temperature Uranium Axis

$$\begin{aligned}T_a &= T_s + \Delta T_{rod} \\ &= 365 + 267 \\ &= 632^\circ\text{C}\end{aligned}$$

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TABLE I (Revised)

Tube
Sample

1	2	3	4	5
A313	A312	A321	A223	B231
A231	A311	A221	A322	B232 None
A232	A213	A222	A323	B233 None
A333	A332	A241	A243	B331 None
A211	A331	A242	A342	B332 None
A212	A233	A341	A343	B333 None
		A042		

Replace with
21's or
possible 23's
if the 33's made
extra one not OK

get
extra
32 & 34
in

31
32
22

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TABLE II (REVISED)

Samples	Cladding Inches	Power Req'd kw/ft	Cladding Temperatures - °C				Exposure $\frac{MWD}{T}$
			Axial Desired Calculated		Cladding Surface Desired Calculated		
A21(1-3)	0.020	24	250	264	500	514	1500
A22(1-3)	0.020	33	250	273	600	603	1500
A23(1-3)	0.020	24	350	354	600	604	1500
A24(1-3)	0.020	33	350	378	↓700	722	1500
A31(1-3)	0.030	24	250	249	500	526	1500
A32(1-3)	0.030	33	250	257	600	624	1500
A33(1-3)	0.030	24	350	354	600	621	1500
A34(1-3)	0.030	33	350	359	↓700	726	1500
B23(1-3)	0.020	24	350	354	600	604	3000
B33(1-3)	0.030	24	350	354	600	621	3000
C22(1-3)	0.020	33	250	273	600	603	5000
C23(1-3)	0.020	24	350	354	600	604	5000
C32(1-3)	0.030	33	250	257	600	624	5000
C33(1-3)	0.030	24	350	354	600	621	5000

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TABLE III (Revised)

Samples	D ₁ inches	A inches	Zr-2 ID-inches	Sleeve OD-inches	D ₂ inches
A21	0.864	0.163			0.864
A22	0.763	0.213			0.763
A23	0.960	0.115	0.750	0.852	0.750
A24	0.914	0.138			0.914
A31	0.875	0.157			0.815
A32	0.772	0.115			0.772
A33	0.960	0.209	0.750	0.892	0.750
A34	0.922	0.134			0.922
B23	0.960	0.115	0.750	0.852	0.750
B33	0.960	0.209	0.750	0.892	0.750
C22	0.763	0.213			0.763
C23	0.960	0.115	0.750	0.852	0.750
C32	0.772	0.115			0.772
C33	0.960	0.209	0.750	0.892	0.750

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VII IRRADIATION CONDITIONS

1. Same

2. Tube power req'd

3 tubes at 700 $\frac{\text{kw}}{\text{tube}}$

2 tubes at 960 $\frac{\text{kw}}{\text{tube}}$

3. Time of Exposure

Tube	1	68	days
	2	68	
	3	50	
	4	50	
	5	136	

4. Temperatures - °C

<u>Sample</u>	<u>Uranium Axial</u>	<u>Cladding Surface</u>	<u>Capsule Surface</u>	<u>local Coolant</u>
A21	514	264	50	15
A22	603	273	63	15
A23	604	354	50	15
A24	722	378	63	15
A31	526	249	50	15
A32	624	257	63	15
A33	621	354	50	15
A34	726	359	63	15
B23	604	354	50	15
B33	621	354	50	15
C22	603	273	63	15
C23	604	354	50	15
C32	624	257	63	15
C33	621	354	50	15

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CALCULATED TEMPERATURES
FOR FOUR TUBE LOADING

(See HW 58625 for additional temperatures)

These temperatures are based on the assumption that the power generation will be the same for each capsule. In practice the flux distribution will cause an alteration in these temperatures.

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Sample A22

$$\Delta T_{\text{rod}} = \Delta T_{\text{conduction}} + \Delta T_{\text{zr-o bond}} + \Delta T_{\text{zr cladding}}$$

$$\begin{aligned}\Delta T_o &= \frac{Q}{4\pi k_i} \\ &= \frac{(33)(3413)}{4\pi(21.3)(1.8)} \\ &= 234^\circ\text{C}\end{aligned}$$

$$\begin{aligned}Q &= 33 \frac{\text{KW}}{\text{ft}} \\ k_i &= 21.3 \frac{\text{Btu}}{\text{hr ft}^\circ\text{F}}\end{aligned}$$

$$\begin{aligned}\Delta T_{\text{zr-o}} &= \frac{Q}{h_i A} \\ &= \frac{(33)(3413)(12)}{(30,000)(\pi)(0.570)(1.8)} \\ &= 14^\circ\text{C}\end{aligned}$$

$$\begin{aligned}\Delta T_{\text{zr}} &= \frac{Q}{2\pi k_z} \ln \frac{d_o}{d_i} \\ &= \frac{(33)(3413)(0.0677)}{2\pi(8.2)(1.8)} \\ &= 82^\circ\text{C}\end{aligned}$$

$$\begin{aligned}\ln \frac{d_o}{d_i} &= \ln \frac{0.610}{0.570} \\ &= 0.0677\end{aligned}$$

$$\Delta T_{\text{rod}} = 330^\circ\text{C}$$

$$\Delta T_{\text{NaK}} = 160^\circ\text{C}$$

$$\Delta T_{\text{al}} = 50^\circ\text{C}$$

$$\Delta T_w = 48^\circ\text{C}$$

$$T_c = 15 + 48 = 63^\circ\text{C}$$

$$T_s = 63 + 50 + 160 = 273^\circ\text{C}$$

$$T_a = 273 + 330 = 603^\circ\text{C}$$

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Sample A23

$$\dot{Q} = 24 \frac{\text{KW}}{\text{ft}^2}$$
$$K_1 = 20.1 \frac{\text{Btu}}{\text{m}^2 \cdot \text{ft} \cdot ^\circ\text{F}}$$

$$\Delta T_{\text{rod}} = 250^\circ\text{C}$$

$$\Delta T_{\text{NaK1}} = 79^\circ\text{C}$$

$$\Delta T_{\text{ev-sleeve}} = 169^\circ\text{C}$$

$$\Delta T_{\text{NaK2}} = 35^\circ\text{C}$$

$$\Delta T_{\text{A2}} = 25^\circ\text{C}$$

$$\Delta T_w = 35^\circ\text{C}$$

$$T_c = 50^\circ\text{C}$$

$$T_s = 50 + 25 + 35 + 169 + 79 = 358$$

$$T_a = 358 + 250 = 608$$

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Sample A 31

$$\Delta T_{rod} = \Delta T_u + \Delta T_{ev-u} + \Delta T_{ev}$$

$$Q = 24 \frac{KW}{ft}$$

$$K_i = 20.1 \frac{Btu}{in-ft-^{\circ}F}$$

$$\Delta T_u = \frac{Q}{4\pi K_i} =$$

$$= \frac{(24)(3413)}{4\pi(20.1)(1.8)}$$

51912

$$= 180^{\circ}C$$

$$\Delta T_{ev-u} = \frac{Q}{h_i A}$$

$$= \frac{(24)(3413)(12)}{(30,000)(\pi)(0.570)(1.8)}$$

982944

$$= 10^{\circ}C$$

$$\Delta T_{ev} = 87^{\circ}C$$

$$\underline{\Delta T_{rod} = 277^{\circ}C}$$

$$\Delta T_{Nek} = 171^{\circ}C$$

$$\Delta T_{Ae} = 28^{\circ}C$$

$$\Delta T_w = 35^{\circ}C$$

$$T_c = 50^{\circ}C$$

$$T_s = 50 + \cancel{35} + 28 + 171 = \overset{249}{284}^{\circ}C$$

$$T_a = \overset{249}{284} + 277 = 526^{\circ}C$$

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Sample A32

$$\Delta T_o = 234^\circ\text{C}$$

$$\Delta T_{\text{er-o}} = 14^\circ\text{C}$$

$$\Delta T_{\text{er}} = 119^\circ\text{C}$$

$$\Delta T_{\text{rod}} = 367^\circ\text{C}$$

$$\Delta T_{\text{NaK}} = 145^\circ\text{C}$$

$$\Delta T_{\text{Aa}} = 49$$

$$\Delta T_w = 48$$

$$T_o = 15 + 48 = 63^\circ\text{C}$$

$$T_s = 63 + 49 + 145 = 257^\circ\text{C}$$

$$T_a = 257 + 367 = 624^\circ\text{C}$$

$$Q = 33 \frac{\text{KW}}{\text{ft}}$$

$$K_i = 21.3 \frac{\text{Btu}}{\text{hr-ft-}^\circ\text{F}}$$

DATE

FILMED

8/16/94

END