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HAPO Irradiation of Capsules Containing
UO₂ Specimens.

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HAPO IRRADIATION OF CAPSULES CONTAINING UO₂ SPECIMENS

-- H.W. Newkirk, M.K. Millhollen, D.W. Brite

INTRODUCTION

A knowledge of the effect of reactor irradiation on the properties of UO₂ is relevant to the design and evaluation of UO₂ fuel elements for the PRTR. Of particular interest is the effect of reactor irradiation on the thermal conductivity of sintered UO₂ and the type, mechanism, and extent of radiation damage in sintered UO₂. In the latter case the study of fractured surfaces of irradiated UO₂ specimens is a method of determining the extent of radiation damage. It is the purpose of this report to propose an irradiation test of a number of capsules containing UO₂ thermal conductivity and fractography specimens.

OBJECTIVE

The objectives of this test are to determine:

1. The effect of reactor irradiation on the thermal conductivity of sintered UO₂.
2. The type, mechanism and extent of radiation damage in sintered UO₂.

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The Ceramic Fuels Development Operation will fabricate the specimens and assemble the irradiation capsules. The Irradiation Testing Operation will conduct the irradiations at accumulated exposures of 10,000 MWD/T and at intermediate levels. The Battelle Memorial Institute will measure the thermal conductivity of the unirradiated and irradiated specimens. The Physical Metallurgy Unit will study the fractured surfaces of the unirradiated and irradiated fractography specimens.

BASIS AND JUSTIFICATION

The trend in current reactor design is toward higher coolant temperatures. Fuel development engineers are considering using UO_2 in high temperature water-cooled reactors. Its principal advantages are: (1,2) 2

1. High melting point, 2750°C.
2. Chemical inertness to high temperature water.
3. Dimensional stability to at least 25,000 MWD/T.
4. Easily fabricated into a variety of sizes and shapes.

At the present time many UO_2 fuel element geometries and sizes are being studied. (3,4) Sufficient data is available to indicate the general stability of the fuel element containing UO_2 . (5,6) The thermal conductivity of sintered UO_2 and the effect of reactor irradiation on this property is of prime importance in the calculation of heat flow and resultant core temperatures in experimental fuel elements. The data presently available is incomplete and the values published (7-12) differ by as much as 30%. A knowledge of the mechanism and extent of radiation damage in UO_2 is relevant to a basic understanding of the in-reactor behavior of fuel elements containing sintered UO_2 .

- (1) Eichenberg, JD, Frank, PW, Kisiel, TJ, Lustman, B., and Vogel, KH, "Effects of Irradiation on Bulk UO_2 ", WAPD-183, Paris Fuel Element Technology Conference (1957) (Unclassified)
- (2) Belle, J and Lustman, B, "Properties of UO_2 ", WAPD-184, September, 1957 (Unc.)
- (3) Fryar, RM and Staff, "Plutonium Recycle Program", HW-50700, June 12, 1957 (Unc.)
- (4) Hanford Laboratories Staff, "Annual Report, Plutonium Recycle Program", HW-52000, September 20, 1957 (Unclassified)
- (5) Roake, WE, "I&E Cooled UO_2 Slug", HW-47604RD, December 21, 1956 (SRD); "Defected UO_2 Slug, GEH-4F", HW-48514, February 11, 1957 (Unclassified); "M-388 Clad I&E Cooled UO_2 Slugs, GEH-4G", HW-49662, April 15, 1957 (Unclassified)
- (6) Roake, WE and Newkirk, HW, "HAPO Irradiation of M-388 Clad, Tubular UO_2 Fuel Elements", HW-52458, July 22, 1957 (Unclassified)
- (7) Kingery, WD, J. Francl, RL Coble and T Vasilos, "Thermal Conductivity I: Data for Several Pure Oxide Materials Corrected to Zero Porosity", J. Am. Ceramic Society 37 (2) 107-110 (1954)
- (8) Weeks, JL, Private Communication to WA Labertson and JH Handwerk, "The Fabrication and Physical Properties of Urania Bodies", ANL-5053, p. 10, February, 1956
- (9) Westphal, RC, "Thermal Conductivity of Reactor Fuel Element Materials", AECD-3864, June 23, 1954 (Unclassified)
- (10) Hedge, JC, "Measurement of the Thermal Conductivity of UO_2 ", AECU-3381, September 20, 1956 (Unclassified)
- (11) PR-CM-11, AECL, Chemistry & Metallurgy Div., Progress Rpt., July 1, 1957 (OUO)
- (12) JE Flinta, "Thermal Conductivity of UO_2 ", Paris Fuel Element Technology Conference, Paris, France, November, 1957 (Unc.)

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PROCEDURES

Irradiation Capsule Fabrication

The UO_2 specimens were extruded, hydrostatically pressed and sintered to various densities in the range 86-98% of the theoretical density according to the methods discussed in HW-51747 (13) and HW-51770 (14). The specimens were ground to 0.248" OD x 3.00" long and assembled into three density ranges, i.e., 86-90, 90-93, 93-98%. Two specimens from each range were chosen for the thermal conductivity test. After marking, the specimens were inserted into six of the eight numbered positions in the irradiation capsule holder. The fractography specimens, chosen from the low density and high density ranges, and containing a 0.0625" wide x 0.0625" deep circumferential groove midway along the length of the specimen, were inserted in the remaining two positions of the irradiation capsule holder. See Figures 1 and 2. Pertinent information concerning the specimens is given in Appendix III. Representative specimens were chosen for pre-irradiation testing and examination. The capsules were closed by inert gas shielded arc welding after filling the void spaces with helium. All welds were X-rayed and the capsules helium-leak tested, water boiled for eight hours and re-helium leak tested. No abnormal leakage or weight changes were observed. Figure 3 illustrates two of the eight completed irradiation capsules. Pertinent information covering the design of the irradiation capsules is given in Appendix II.

Irradiation

We request that an irradiation test be initiated in which the eight capsules are located within a neutron flux of 5×10^{13} NV. Two capsules should be discharged after 1,000 MWD/T. The test should be continued if post-irradiation examination of the UO_2 specimens is favorable. The third and fourth capsules should be discharged after 3,000 MWD/T, the fifth and sixth capsules after 5,000 MWD/T and the final two capsules after an exposure of 10,000 MWD/T. Pertinent information concerning this irradiation proposal is given in Appendix I.

Hazards

UO_2 compacts are reported to be resistant to erosion and are stable to oxidation over long periods in degassed water and steam at neutral and high pH. Exposure to water containing oxygen causes the formation of a surface scale of higher oxide. (15) The irradiation capsules were tested and were found to be leak tight. Calculated fission gas pressures are fifteen times less than the maximum allowable cladding working pressure. Hence, very little hazard is involved in this irradiation.

- (13) DR Stenquist and RJ Anicetti, "Extrusion of UO_2 Fuel Cores," HW-51747, December 1, 1957 (Unclassified)
- (14) HW Newkirk and RJ Anicetti, "Fabrication of Uranium Dioxide Fuel Element Shapes by Hydrostatic Pressing," HW-51770, August 1, 1957 (Unclassified)
- (15) AJ Belle and B Lustman, "Properties of UO_2 ", WAPD-184, September, 1957, pp 55-59 (Unclassified)

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Post-Irradiation Measurements

Following irradiation and discharge, the capsules will be shipped to the HAP0 Radiometallurgy facility. The capsules will be opened and the specimens removed. The irradiated thermal conductivity specimens will be shipped to the Battelle Memorial Institute. The fractography specimens will be examined by Physical Metallurgy personnel. Samples from the fractography specimens will be used for burn-up analysis.

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APPENDIX I

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SUMMARY OF PROPOSED IRRADIATION CONDITIONS

Maximum power generation of capsule, Q (watts/in)	314
Maximum heat flux of capsule, H (BTU/(hr)(ft ²))	34,100
Bulk inlet water temperature, t_w (°F)	60
Water film coefficient, h (BTU/(hr)(ft ²)(°F))	2,430
Water film temperature drop, ΔT_w (°F)	14
Outside cladding temperature, T_{c_o} (°F)	74
Cladding temperature drop, ΔT_c (°F)	16
Interior cladding temperature, T_{c_1} (°F)	90
UO ₂ - aluminum interface heat transfer coefficient, h_1 (BTU/(hr)(ft ²)(°F))	6,000
UO ₂ - aluminum interface temperature drop, ΔT_{UO_2-Al} (°F)	9
Minimum outside fuel temperature, T_{f_o} (°F)	99
UO ₂ specimen temperature drop, ΔT_f (°F)	58
Core temperature of specimen, T_c (°F)	157
Water flow velocity, v (ft/sec)	13.28
Water pressure drop, ΔP (psi)	0.04
Maximum exposure time, λ , days	832
Maximum percentage burnup, β , (%)	1.16
Maximum fission gas produced, F_g (cc)	6.2
Maximum operating fission gas pressure, P (psi)	19
Maximum allowable cladding working pressure, P_a (psi)	288

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THERMAL CALCULATIONS

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Introduction

A. UO₂ Specimen Specifications

Outside diameter, OD (inches)	0.248 ± 0.001
Length of UO ₂ , L, (inches)	3.005 ± 0.001
Weight of UO ₂ , W, (grams)	25.6090
Volume of UO ₂ , V, (cc)	2.379 ± 0.001
Density of UO ₂ , ρ_a , (g/cc)	10.77 ± 0.01
Density of UO ₂ , ρ_{th} , (per cent of theoretical)	98.1 ± 0.1

B. Can Specifications

Outside diameter, OD (inches)	1.440
Inside diameter, ID (inches)	1.340
Wall thickness, Δx_w , (inches)	0.050
Length, L, (inches)	8.70

C. Requested Irradiation Conditions

Unperturbed thermal neutron flux density, $\phi_{(th)}$, (neutrons/(cm ²)(sec))	5 x 10 ¹³
Flux depression, d, (per cent)	2.0
Maximum exposure time, λ (days)	832
Rise factor, f_r	1.0
Cosine factor, f_c	1.0

D. Water Coolant Properties

Bulk inlet water temperature, t_w	60°F (15°C)
Flow rate, W (gal/min)	20
Thermal conductivity of water at 60°F, K_w (BTU/hr,ft,°F)	0.340
Dynamic viscosity of water at 60°F, μ (lbs/hr,ft)	2.731
Density of water at 60°F, ρ_w (lbs/ft ³)	62.4

Capsule Power Generation

The power generation of the capsule, Q, is given by

$$Q \text{ (watts)} = \phi_{O(th)} (nv) \times (1-d) \times 8 \times V \text{ (cc)} \times \rho_a \text{ (g/cc)} \times ZU \times \frac{Z_{U-235} \times 4.315 \times 10^{-11} \text{ (watts} \cdot \text{cm}^2 \cdot \text{sec)} \text{ g.neutrons}}{1 - Z_{U-235}}$$

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where

Uranium in UO_2 , $Z_U = 88.15$ w/o

U-235 in natural uranium, $Z_{U-235} = 0.71$ w/o

$$Q = \frac{(5 \times 10^{13})(1-0.02)(19)(10.77)(0.8815)(0.0071)(4.315 \times 10^{-11})}{1 - 0.0071}$$

$$Q = 2,735 \text{ watts} + 8.70 \text{ inches}$$

$$Q = 314 \text{ watts/inch}$$

Capsule Heat Flux

The heat flux, H, of the capsule is given by

$$H \text{ (BTU/(hr)(ft}^2\text{))} = \frac{Q \text{ (watts/in)} \times 144 \text{ (in}^2\text{/ft}^2\text{)} \times 3.413 \text{ (BTU/(hr)(watt))}}{3.142 \times OD \text{ (in)}}$$

$$H = \frac{(314)(144)(3.413)}{(3.142) \times (1.440)}$$

$$H = 34,100 \text{ BTU/(hr)(ft}^2\text{)}$$

Heat Transfer

A. Water Film Coefficient

The water film heat transfer coefficient, h, for the turbulent flow of water through the process tube is given by

$$h \text{ (BTU/(hr)(ft}^2\text{)(}^\circ\text{F))} = 0.023 \frac{K_w}{De} \left[N_{re} \right]^{0.8} \left[N_{pr} \right]^{0.4}$$

where

$$\text{Equivalent diameter, } De \text{ (ft)} = 4 Af/b$$

$$\text{Flow area, } Af \text{ (ft}^2\text{)} = \frac{\pi \left[\left(\text{Inside radius of Process tube} \right)^2 - \left(\text{Outside diameter of capsule} \right)^2 \right]}{144 \text{ (in}^2\text{/ft}^2\text{)}}$$

$$\text{Wetted perimeter, } b \text{ (ft)} = 3.142 \times OD \text{ (ft)}$$

$$\text{Reynolds number, } N_{re} = \frac{De G}{\mu}$$

$$\text{Mass velocity, } G \text{ (lb)/(hr)(ft}^2\text{)} = \frac{W \text{ (gal/min)} \times 8.33 \text{ (lbs/gal)} \times 60 \text{ (min/hr)}}{Af \text{ (ft}^2\text{)}}$$

$$\text{Prandtl number} = N_{pr}$$

The heat transfer coefficient for water flowing through a channel with an equivalent diameter of 0.25 inches has been plotted as a function of water

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temperature and mass velocity. A correction factor has also been plotted for equivalent diameters other than 0.25 inches⁽¹⁶⁾. Thus

$$Af = 3.142 \left[(0.82)^2 - (0.72)^2 \right]$$

$$Af = 0.00336 \text{ ft}^2$$

and

$$b = (3.142)(0.120)$$

$$b = 0.378 \text{ ft}$$

Therefore

$$D_e = \frac{(4)(0.00336)}{(0.378)}$$

$$D_e = 0.036 \text{ (ft)} \times 12 \text{ (in/ft)}$$

$$D_e = 0.431 \text{ inches}$$

Now

$$G = \frac{(20)(8.33)(60)}{(0.00336)}$$

$$G = 2.97 \times 10^6 \text{ lb/(hr)(ft}^2\text{)}$$

From the graph on p. 48, footnote (16),

$$h_{0.25} = 2700 \text{ BTU/(hr)(ft}^2\text{)(}^\circ\text{F)}$$

and

$$\text{Correction factor} = 0.9$$

Hence

$$h_{0.431} = (2700)(0.9)$$

$$h_{0.431} = 2430 \text{ BTU/(hr)(ft}^2\text{)(}^\circ\text{F)}$$

B. Water Film Temperature Drop

The temperature drop across the water film, ΔT_w , is given by

$$\Delta T_w = T_2 - T_1 = \frac{Q \text{ (watts/in)} \times 3.413 \text{ (BTU/(hr)(watt)} \times 144 \text{ (in}^2\text{/ft}^2\text{))}}{h \text{ (BTU/(hr)(ft}^2\text{)(}^\circ\text{F)} \times OD \text{ (in)} \times 3.142}$$

(16) Reactor Handbook, "Engineering", Vol. 2, p. 48, May 1955, AECR-3646

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$$\Delta T_w = \frac{(314)(3.413)(144)}{(2430)(1.44)(3.142)}$$

$$\Delta T_w = 14^\circ \text{F}$$

C. Cladding Temperature Drop

If we neglect the can-specimen holder interface temperature drop, an approximation of the temperature drop across the cladding material, can + specimen holder + rail,

ΔT_c , is given by

$$\Delta T_c = T_3 - T_2 = Q \text{ (watts/in)} \times \Delta X_c \text{ (in)} \times 3.412 \text{ (BTU/(hr)(watt))} \times 12 \text{ (in/ft)}$$

where

$$\text{Average area, } A \text{ (in}^2\text{/in)} = \pi \sqrt{\frac{(\text{O.R.})(\text{I.R.})}{1 \text{ (in)}}}$$

$$A = \frac{3.142 \sqrt{(0.720)(0.438)}}{1}$$

$$A = 1.76 \text{ in}^2\text{/in}$$

Thermal conductivity of cladding material, $K_c \text{ (BTU/(hr)(ft)(}^\circ\text{F))} = 128$

Clad wall thickness, $\Delta X_c \text{ (in)} = 0.282$

Therefore,

$$\Delta T_c = \frac{(314)(0.282)(3.412)(12)}{(1.76)(128)}$$

$$\Delta T_c = 16^\circ \text{F}$$

D. UO₂-Aluminum Interface Temperature Drop

The temperature drop across the UO₂-Aluminum interface is given by

$$\Delta T_{\text{UO}_2\text{-Al}} = T_4 - T_3 =$$

$$\frac{Q \text{ (watts/in)} \times 3.412 \text{ (BTU/(hr)(watt))} \times 144 \text{ (in}^2\text{/ft}^2\text{)}}{h_1 \text{ (BTU/(hr)(ft}^2\text{)(}^\circ\text{F))} \times ID_c \text{ (in)} \times 3.142}$$

where

UO₂-Aluminum interface heat transfer coefficient,

$$h_1 \text{ (BTU/(hr)(ft}^2\text{)(}^\circ\text{F))} = 6,000$$

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Inside diameter of clad, ID_c (in) = 0.876

Therefore

$$\Delta T_{UO_2-Al} = \frac{(314)(3.412)(144)}{(6,000)(0.876)(3.142)}$$

$$\Delta T_{UO_2-Al} = 9^\circ F$$

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E. Temperature Drop Through Specimen and Specimen Core Temperature

The temperature drop through a specimen, ΔT_f , is given by

$$\Delta T_f = T_5 - T_4 = T_{\text{surface}} (^\circ C) + 350 \left(e^{\frac{Q}{1,388} \frac{(\text{watts})}{\text{in}}} - 1 \right)$$

where

Surface temperature of specimen, $T_{\text{surface}} = 37^\circ C$ ($99^\circ F$)

Power generation of specimen, Q (watts/in) = 114

Therefore,

$$\Delta T_f = 37 + 350 \left(e^{\frac{(114)}{1,388}} - 1 \right)$$

$$\Delta T_f = 32^\circ C$$
 ($58^\circ F$)

and the core temperature of the specimen, T_c , is

$$T_c = 69^\circ C$$
 ($157^\circ F$)

HYDRAULICS

Flow velocity

The water coolant flow velocity, v , past the capsule is given by

$$v \text{ (ft/sec)} = \frac{W \text{ (gal/min)} \times 8.335 \text{ (lbs/gal)}}{A_f \text{ (ft}^2\text{)} \times \rho_w \text{ (lbs/ft}^3\text{)} \times 60 \text{ (sec/min)}}$$

$$v = \frac{(20)(8.335)}{(0.00336)(62.4)(60)}$$

$$v = 13.28 \text{ ft/sec}$$

Water Pressure Drop

The pressure drop, ΔP , over the length of the capsule is given by

$$\Delta P \text{ (lb/ft}^2\text{)} = \frac{f \times b \text{ (lb/(hr)(ft}^2\text{))}^2 \times L \text{ (ft)}}{2 \times \rho_w \text{ (lb/ft}^3\text{)} \times g \text{ (ft/sec}^2\text{)} \times D_e \text{ (ft)} \times (3600 \text{ sec/hr})^2}$$

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where

Friction factor, $f = 0.02$

Acceleration of gravity, $g \text{ (ft/sec}^2\text{)} = 32.2$

$$\Delta P = \frac{(0.02)(2.97 \times 10^6)(0.725)}{(2)(62.4)(32.2)(0.431)(3600)^2}$$

$$\Delta P = \frac{5.72 \text{ lbs/ft}^2}{144 \text{ (in}^2\text{/ft}^2\text{)}}$$

$$\Delta P = 0.04 \text{ psi}$$

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FISSION GAS CALCULATIONS

Maximum Exposure Time

The maximum specimen exposure time, λ , is given by

$$\lambda \text{ (days)} = \frac{W_u \text{ (g)} \times E \text{ (MWD/T)}}{Q \text{ (megawatts)} \times 454 \text{ (g/lb)} \times 2000 \text{ (lbs/ton)}}$$

Where

Weight of U as UO_2 , $W_u \text{ (g)} = 22.6$, and reactor exposure, $E \text{ (MWD/T)} = 10,000$

$$\lambda = \frac{(22.6)(10,000)}{(3.42 \times 10^{-6})(454)(2000)}$$

$$\lambda = 832 \text{ days}$$

Maximum Burnup

The maximum fraction of uranium atoms converted to fission products, β_f , is given by

$$\beta_f = E \text{ (MWD/T)} \times 1.16 \times 10^{-6} \times 100$$

$$\beta_f = (10,000)(1.16 \times 10^{-6})(100)$$

$$\beta_f = 1.16\%$$

Maximum Total Fission Gas

The volume of fission gas produced as a result of irradiation, F_g , measured under standard conditions of temperature and pressure is given by

$$F_g \text{ (cc)} = \frac{\beta_{\text{U-235}} \text{ (U-235 fissioned/T)} \times W_u \text{ (g)}}{2,000 \text{ (lbs/T)} \times 454 \text{ (g/lb)} \times F_{\text{U-235}} \text{ (U-235 fissioned/cc of gas)}}$$

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where

$$\begin{aligned} & \text{U-235 Burnup, } \beta \text{U-235 (U-235 fissioned/T)} \\ & = E \text{ (MWD/T)} \times 2.68 \times 10^{21} \text{ (U-235 fissioned/MWD)} \end{aligned}$$

$$\beta \text{U-235} = (10,000)(2.68 \times 10^{21})$$

$$\beta \text{U-235} = 2.68 \times 10^{25} \text{ U-235 fissioned/T}$$

and

$$\text{U-235 Fission gas production, } F_{\text{U-235}} \text{ (U-235 fissioned/cc of gas)} = 1.073 \times 10^{20}$$

Therefore,

$$F_g = \frac{(2.68 \times 10^{25})(22.6)}{(2,000)(454)(1.073 \times 10^{20})}$$

$$F_g = 6.2 \text{ cc}$$

Maximum Gas Pressure

The maximum gas pressure in the capsule prior to discharge, P, is given by the ideal gas law

$$P \text{ (atm)} = \frac{n(\text{moles}) \times R \text{ (cc-atm, deg}^{-1} \text{ mole}^{-1}) \times T \text{ (}^{\circ}\text{K)}}{V \text{ (cc)}}$$

where

$$\text{Gas constant, } R \text{ (cc, atm, deg}^{-1} \text{ mole}^{-1}) = 82.057$$

$$P = \frac{(2.8 \times 10^{-4})(82.057)(342)}{6.2}$$

$$P = 1.3 \text{ atm} \times 14.7 \text{ (psi/atm)}$$

$$P = 19 \text{ psi}$$

Maximum Allowable Pressure in Capsule

The maximum allowable working stress, P_a , assuming the applicability of the ASME Boiler Code, Par. P-22, Sect. 1, is given by

$$P_a = S \text{ (psi)} \left[\frac{2 \times \Delta X_w \text{ (in)} - 0.027 \times \text{O.D. (in)} - 2e}{\text{OD (in)} - (2 \times \Delta X_w \text{ (in)} - 0.027 \times \text{OD (in)}) - 2e} \right]$$

where

yield strength of M-388 aluminum, S (psi) = 6,500
(0.2% offset and 0.5 S safety factor)

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and
concentricity factor, $2e = 0$

Therefore,
$$P_a = 6,500 \left[\frac{(2)(0.050)}{(1.440)} - \frac{(0.027)(1.440)}{(2)(0.050) - (0.027)(1.440)} \right]$$

$$P_a = 288 \text{ psi}$$

APPENDIX II

IRRADIATION CAPSULE DESIGN

The capsules, Figures 1-3, were designed for the convenient removal of irradiated specimens, and specimen mechanical stability. They consist essentially of a 2S aluminum specimen holder and an M-388 aluminum alloy can. The specimen holder contains two groups of four longitudinal slots arranged radially at 90° around the axis of the holder and separated by means of a shelf. The UO_2 specimens are held within the slots by means of stainless steel springs and 2S aluminum end plugs at each end and a 2S aluminum rail along the length of the specimen. After irradiation the specimens are removed by cutting off both ends of the capsule in such a manner that the ends of the specimen holder are revealed. The holder can then be pushed out of the can. The specimens are recovered after first removing the end plugs, springs and rails.

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APPENDIX III**DECLASSIFIED**UO₂ THERMAL CONDUCTIVITY AND FRACTOGRAPHY SPECIMENSFuel Element A

<u>Specimen No. & Position No.</u>	<u>Test</u>	<u>Weight, g.</u>	<u>Length, inches</u>	<u>Density, g/cc</u>	<u>% Theoretical Density (UO₂ 2.00 = 10.97 g/cc)</u>
1	T.C.*	23.1814	3.024	9.68	88.3
2	T.C.	23.9456	3.012	10.04	91.6
3	T.C.	24.6391	3.013	10.33	94.2
4	F.R.**	23.3868	3.033	9.74	88.6
5	T.C.	23.6096	3.033	9.83	89.7
6	F.R.	25.6090	3.005	10.77	98.1
7	T.C.	24.8905	3.018	10.42	95.0
8	T.C.	24.1574	3.015	10.12	92.3

Fuel Element B

9	T.C.	23.3140	3.030	9.72	88.6
10	T.C.	24.0342	3.012	10.08	91.9
11	T.C.	24.6495	3.015	10.33	94.2
12	F.R.	23.3043	3.035	9.70	88.4
13	T.C.	25.0229	3.015	10.49	95.6
14	T.C.	24.1340	3.027	10.07	91.8
15	T.C.	23.4735	3.035	9.77	89.1
16	F.R.	24.6827	3.004	10.38	94.6

Fuel Element C

17	T.C.	23.4555	3.014	9.83	89.6
18	T.C.	23.9660	3.000	10.09	92.0
19	T.C.	25.0763	3.015	10.51	95.8
20	F.R.	23.5846	3.042	9.79	89.3
21	F.R.	24.8822	3.014	10.43	95.1
22	T.C.	24.6825	3.019	10.33	94.2
23	T.C.	23.9658	3.009	10.06	91.7
24	T.C.	23.6565	3.027	9.87	90.0

Fuel Element D

25	T.C.	23.7207	3.037	9.87	90.0
26	T.C.	24.0025	3.018	10.05	91.6
27	T.C.	24.8532	3.013	10.42	95.0
28	F.R.	23.4482	3.026	9.79	89.2
29	T.C.	24.9876	3.012	10.48	95.5
30	T.C.	24.2500	3.031	10.11	92.1
31	T.C.	23.0930	3.032	9.62	87.7
32	F.R.	24.9268	3.005	10.48	95.5

* T.C. - Thermal Conductivity

** F. R. - Fractography

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<u>Specimen No. & Position No.</u>	<u>Test</u>	<u>Weight, g</u>	<u>Length, inches</u>	<u>Density, g/cc</u>	<u>% Theoretical Density (UO₂ = 10.97 g/cc)</u>
<u>Fuel Element E</u>					
33	T.C.	22.9231	3.040	9.53	86.8
34	T.C.	23.8954	3.010	10.03	91.4
35	T.C.	24.8611	3.011	10.43	95.1
36	F.R.	23.7760	3.032	9.91	90.3
37	T.C.	23.3851	3.025	9.77	89.0
38	F.R.	25.1435	3.013	10.54	96.1
39	T.C.	24.5946	3.008	10.33	94.2
40	T.C.	23.9573	3.012	10.05	91.6
<u>Fuel Element F</u>					
41	T.C.	23.2690	3.015	9.75	88.9
42	T.C.	24.2683	3.009	10.19	92.9
43	T.C.	24.9491	3.012	10.46	95.4
44	F.R.	23.7710	3.012	9.97	90.9
45	T.C.	24.7070	3.007	10.38	94.6
46	T.C.	23.7798	3.009	9.98	91.0
47	T.C.	23.4133	3.037	9.74	88.8
48	F.R.	25.0063	3.014	10.48	95.6
<u>Fuel Element G</u>					
49	T.C.	23.6715	3.038	9.84	89.7
50	T.C.	24.1876	3.013	10.14	92.5
51	T.C.	24.9878	3.013	10.48	95.5
52	F.R.	23.4751	3.022	9.81	89.5
53	T.C.	23.3628	3.018	9.78	89.2
54	F.R.	25.0353	3.012	10.50	95.7
55	T.C.	24.8498	3.012	10.42	95.0
56	T.C.	24.0755	3.021	10.07	91.8
<u>Fuel Element H</u>					
57	T.C.	22.8665	3.012	9.59	87.4
58	T.C.	24.2585	3.017	10.16	92.6
59	T.C.	25.0102	3.011	10.49	95.7
60	F.R.	23.4517	3.018	9.82	89.5
61	T.C.	23.3585	3.034	9.73	88.7
62	F.R.	24.6800	3.013	10.35	94.3
63	T.C.	24.8187	3.015	10.40	94.8
64	T.C.	23.9134	3.019	10.01	91.2

Note: Outside diameter on all specimens - 0.248 ± 0.001 inches
The density values are estimated to be uncertain to ± 0.01 g/cc.

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CAN & CAP-M-388 AI

SPECIMEN HOLDER

NOTE: ALL MATERIAL 2S AI
UNLESS SPECIFIED

FIGURE 1

Irradiation Capsule Containing UO₂ Specimens

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FIGURE 2
Irradiation Capsule Disassembled

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FIGURE 3

Irradiation Capsule Assembled

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