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SUBJECT: Calculations for Irradiation of Natural UO_2-ThO_2 (Revised)

TO: R. V. McCord

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Abstract

Calculations are given for eighteen stainless steel clad helium bonded specimens of UO_2-ThO_2 containing normal U to be placed in 6 holes in a holder in a position of the ORR not to exceed a peak unperturbed flux of 4×10^{14} n/cm²/sec and irradiated to a peak nvt of 1.96×10^{21} neutrons/cm².

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GEOMETRY

Pellet Diameter	0.2635"
Tube OD	0.3125"
Tube ID	0.2725"
Pellet - Tube Wall Gap	0.0045"
Pellet Cross-section	0.0545 in. ²
Tube Inside Cross Section	0.0582 in. ²
Tube Wall	0.020" thick
Specimen Cross Section	0.0766 in. ²
Specimen Length (total)	7.25"
Specimen Active Length	5.875"
Specimen Volume	9.11 cc
Active Volume	5.16 cc
End Plug Length	0.625" (each)
End Plug Volume	~1.6 cc (total)
Active Peripheral Surface	4.85 in. ²

WEIGHTS

Specimen Active Section	5.16 x 9.3 g/cc = 48 g
UO ₂ per Specimen	(48)(0.0454) = 2.18 g
ThO ₂ per Specimen	(48)(0.9546) = 45.7 g
U per Specimen	1.92 g
U-235 per Specimen	0.0136 g
Th per Specimen	40.2 g
SS per Specimen (7.9) $\sqrt{1.6 + (3.14 \times 0.3 \times 0.02)(16.4)}$	7 = 15 g
Al per Specimen (1/18 of holder)	1758/18 = 98 g

FLUX

Peak unperturbed assumed: 4×10^{14} n/cm²/sec
 from CF 59-2-91, flux at surface of specimen = $(0.6)(4 \times 10^{14}) = 2.4 \times 10^{14}$ n/cm²/sec.
 Conservatively assume uniform flux in specimen = 2.4×10^{14} n/cm²/sec.

POWER

Peak power will occur at end of irradiation since we begin with normal U.
 ϕt at end = 1.96×10^{21}

From ORNL-1818: $N_{23} + 13/N_{Th}$ at end = 9.95×10^{-3}
 N_{25}/N_{Th} at end = $(3.2 \times 10^{-4})e^{-(1.96 \times 10^{21})(689 \times 10^{-24})}$
 $= (3.2 \times 10^{-4})(e^{-1.35}) = 8.3 \times 10^{-5}$

Neglect U-235 and Pu-239 contributions to power at end by assuming

$$N_{23}/N_{Th} = 1.00 \times 10^{-2}$$

$$\text{Atoms U-233/specimen at end} = \frac{40.2}{232} \times 6.02 \times 10^{23} \times 10^{-2} = 1.05 \times 10^{21}$$

$$\text{Fission watts/specimen} = \frac{(1.05 \times 10^{21})(2.4 \times 10^{14})(520 \times 10^{-24})}{3.1 \times 10^{10}} = 4220$$

Add 12 watts/g for γ -heating:

$$\gamma \text{ heating watts in specimen} = (12)(48 + 15) = 750$$

$$\text{Total watts/specimen} = 4970$$

$$\text{Total watts in active part of specimen} = 4750$$

$$\text{Total watts to be removed by coolant} = 5920 \text{ (includes } \gamma \text{ heat of holder)/specimen}$$

q/A from pellet surface neglecting axial heat transfer

$$= \frac{4750 \times 3.415 \times 144}{4.85} = 483,000 \text{ Btu/hr/ft}^2$$

ΔT PELLET CENTER TO SURFACE

Assume average $k = 0.0043 \text{ cal/sec cm } ^\circ\text{C}$ which is 1600°C value

$$\frac{\text{watts}}{\text{cc}} = \frac{4750}{5.16} = 921$$

$$(921)(0.239) = 220 \text{ cal/sec/cc}$$

$$\Delta t = \frac{(220)(0.335)^2}{(4)(0.0043)} = 1440^\circ\text{C}$$

CAN ΔT AND CAN OUTSIDE TEMPERATURE

By interpolation from CF 59-2-91 for $q/A = 483,000 \text{ Btu/hr/ft}^2$
 Can outside temperature = 199°F

$$\Delta t \text{ through can} = \frac{(483,000)(0.00167)}{9.4} = 85^\circ\text{F}$$

Can average temperature = 142°F

$142 - 70 = 72^\circ\text{F}$ above loading

THERMAL EXPANSION

SS can: negligible (see CF 59-2-91)

Pellet expansion $9 \times 10^{-6}/^\circ\text{C}$

Assume average pellet temperature of 1600°C

Diameter expands: $9 \times 10^{-6} \times 1600 \times 0.2635 = 0.0037''$

Gap after expansion = $0.0045 - 0.00185 = 0.00265''$

Active length expands: $9 \times 10^{-6} \times 1600 \times 6 = 0.086''$

WATER EXIT TEMPERATURE

$5920 \text{ watts/rod} \times 18 \text{ rods} = 106,000 \text{ watts}$

$(106,000)(3.14) = 334,000 \text{ Btu/hr}$

$v = 0.0596 \text{ ft}^3/\text{sec}$

$(0.0596)(62.3)(3600) = 13,400 \text{ lbs/hr}$

$$\frac{334,000}{13,400} = 25^\circ\text{F temperature rise}$$

If inlet is at 80°F outlet will be 105°F .

GAS RELEASE

From ORNL-1818 at end of irradiation from Th: FP concentration will be
 1 g/kg Th

from U-235 burnup: FP concentration will be 0.24 g/kg Th

from Pu-239 burnup: assume FP concentration of 0.24 g/kg Th

Total FP concentration at end then 1.48 g/kg Th

From ORNL-2127, Part II, Vol. 3, p. 1063

for $\phi = 2 \times 10^{14}$, $t = 1 \times 10^7$

$$(N_{\text{Kr}} + N_{\text{Xe}})/N_{25}^0 = 0.36 \text{ from U-235 fission}$$

$$\text{Assume total } N_{\text{Kr}} + N_{\text{Xe}} = 1.8 (0.36) \left(\frac{1.48}{0.24} \right) = 4.0 \frac{\text{atoms}}{\text{initial U-235 atom}}$$

where the 1.8 is a factor to correct for the difference in U-233 and U-235 fission yield spectra.

$$\text{U-235 atoms initially in specimen} = \frac{0.0136}{235} \times 6.02 \times 10^{23} = 3.48 \times 10^{19}$$

$$\text{Kr + Xe atoms/specimen at end} = (3.48 \times 10^{19})^4 = 1.39 \times 10^{20}$$

$$\frac{\text{Xe}}{\text{Kr}} \text{ atom ratio} = 6.8$$

$$\text{Xe atoms/specimen} = 1.21 \times 10^{20}$$

$$\text{Kr atoms/specimen} = 1.78 \times 10^{19}$$

Allowing for thermal expansion, gas space in specimen at end:

$$= 16.4 \left[(0.0026)(3.14)(0.27)(6) + (0.125 - 0.086)(0.785)(0.27^2) \right]$$

$$= 16.4 (0.0132 + 0.0022) = 0.26 \text{ cc}$$

At time of loading gas space = 0.51 cc

$$\text{mols of gas } n = \frac{Pv}{RT} = \frac{(1)(5.1 \times 10^{-4})}{(0.082)(297)} = 2 \times 10^{-5} \text{ mols}$$

At end:

Gas	Mols in Specimen	Mols in Gas Space for 5% FP Gas Release*	Mol Fraction
He	2×10^{-5}	2×10^{-5}	0.64
Xe	2×10^{-4}	1.0×10^{-5}	0.32
Kr	3×10^{-5}	0.15×10^{-5}	0.04
	2.5×10^{-4}	3.15×10^{-5}	

* Power Reactor Tech., 1, No. 3, p. 30: 0.344" dia UO_2 , 10,900 Mwd/t heat flux 370,000 Btu/hr ft² central temp 2650°C released 5.0% Kr-85.

Effect of Kr on conductivity neglected hereafter

For binary He-Xe Brokaw Method (I&EC 47, 2398, 1955) $a = 0.54$

Assume gap $\Delta t = 1500^\circ\text{F}$

Average gas $t = 892^\circ\text{F}$ (752°K)

$$P = \frac{nRT}{V} = \frac{(3.15 \times 10^{-5})(0.082)(752)}{2.6 \times 10^{-4}} = 7.5 \text{ atm.}$$

Generalized reduced conductivity (Owens and Thodos, AICHE Journal, 3, No. 4, p. 454, 1957)

$$\text{He } T_r = \frac{752}{20} = 37.6$$

$$P_r = \frac{7.5}{9.6} = 0.78$$

$$\text{Xe } T_r = \frac{752}{290} = 2.6$$

$$P_r = \frac{7.5}{58} = 0.13$$

$$\text{He } k = (4.3)(0.036) = 0.155 \text{ Btu/hr/ft/}^\circ\text{F}$$

$$\text{Xe } k = (0.72)(0.0097) = 0.0070 \text{ Btu/hr/ft/}^\circ\text{F}$$

$$k_{sm} = (0.67)(0.155) + (0.33)(0.0070) = 0.106$$

$$\frac{1}{k_{rm}} = \frac{0.67}{0.155} + \frac{0.33}{0.0070} = 47.9$$

$$k_{rm} = 0.0209$$

$$k_m = (0.54)(0.106) + (0.46)(0.0209) = 0.0666$$

Radiative gap heat transfer:

$$q/A = (0.173)(0.8) \left[(22.54)^4 - (7.44)^4 \right] \\ = 0.138 (254,000 - 3,000) = 34,000 \text{ Btu/hr/ft}^2$$

Conductive gap heat transfer:

$$\Delta t = \frac{(483,000 - 34,000) \left(\frac{0.00265}{12} \right)}{0.0666} = 1490^\circ\text{F}$$

Close enough to 1500°F assumed.

SPECIMEN TEMPERATURES

$$\text{Pellet center: } \frac{1490}{1.8} + 1440 + \frac{284 - 32}{1.8} = 830 + 1440 + 140 = 2410^\circ\text{C}$$

This is below melting point of $\sim 3300^\circ\text{C}$. Since 5% of F.P. gas was released with pellet center of 2650°C the gas release has been overestimated and the gap conductivity underestimated.

Pellet surface 970°C

Pellet average 1690°C which is close enough to 1600°C assumed for thermal expansion calculation.

CLAD STRESS

$$P = (7.5)(14.7) = 110 \text{ psi}$$

$$S = \frac{(110)(0.3125)}{(2)(0.020)} = 860 \text{ psi which is well below } 35,000 \text{ psi yield strength of } 304\text{L SS.}$$

PRESSURE DROP

20 psi (same as CF 59-2-91).

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