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A "POISON-FREE" LOADING OF UO_2 AND PU-Al IN THE PRCF WITH D_2O-MODERATOR

V. O. UOTINEN

MAY, 1967

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V. O. Uotinen

INTRODUCTION

The control rods that are used in the D_2O-moderated Plutonium Recycle Critical Facility (PRCF) are of the "shutter" type so that, in their normal "withdrawn" position, there is still a large amount of cadmium in the reactor.[1] Thus, under normal operating conditions the three control rods create three large flux sinks in the reactor. This report describes an experiment that has been conducted to establish a critical configuration with all three control rods and their thimbles removed from the reactor. This experiment determined a critical loading for an essentially "poison-free" core.

The PRCF contained fuel in a two-zone loading, an inner zone of natural uranium oxide[2] and an outer zone of 1.8 wt% Pu-Al.[3] The fuel elements were 19-rod clusters and were arranged in a hexagonal lattice with an 8 in. pitch.

SUMMARY

The "poison-free" critical configuration contained 24 UO_2 fuel elements and 16 Pu-Al fuel elements. With this loading the reactor was critical at a moderator height of 98.15 in. In this control-rod-free loading, measurements were made of the radial distribution of the reaction rate of gold foils. The Westcott epithermal index, r, was determined from a cadmium ratio measurement. Also, the reactivity worth of each control rod was measured as the control rods were reinstalled, one at a time.

A calculation has been performed with the one-dimensional diffusion-theory code HFN[4] to obtain analytical values of the effective multiplication factor and the critical radius for the control-rod-free loading. The calculated effective multiplication factor is ∿0.7% high and the calculated critical radius is ∿2% low.

DESCRIPTION OF FUEL

The UO_2 fuel elements contained natural uranium dioxide. The plutonium in the Pu-Al fuel elements contained 93.55 wt% Pu^{239}, 6.00 wt% Pu^{240}, 0.45 wt% Pu^{241}, and <0.01 wt% Pu^{242}. Each fuel element was a cluster of 19 rods. Each rod was 88 in. long and 0.500 in. in diameter and surrounded by a 0.03 in. thick Zircaloy-2 jacket. A Zircaloy-2 wire wrap, 0.072 in. diam, separated the rods of a cluster.

DESCRIPTION OF CONTROL ROD

Each control rod consists of two concentric aluminum tubes. The inner tube (1.000 in. OD with 0.088 in. wall) travels vertically inside the outer tube (1.315 in. OD with 0.055 in. wall). Both tubes are enclosed in an aluminum thimble with a 1.660 in. OD and a 0.140 in. wall thickness. The outer surfaces of both tubes have alternate 6 in. long regions that are coated with 0.025 in. of cadmium. The reactivity of the PRCF is increased by raising the inner cylinder so that its cadmium sections are shaded from thermal neutrons by the

cadmium on the outer cylinder. The total travel of the inner cylinder from the "shutter closed" position to the "shutter open" position is 6 in.; and the total exposed area of the cadmium sections is cut approximately in half in going from "closed" to "open."

EXPERIMENTAL RESULTS

CRITICAL CONFIGURATIONS

The PRCF was initially loaded to critical with the three control rods at a radius of 24 in. in the reactor (Figure 1). The control rods were removed one at a time and the loading was adjusted at each step to achieve criticality with two, one, and finally with no control rods in the reactor (Figures 2, 3, and 4).

The critical configurations are described in Table I. Listed for each loading are the positions of control rods, the height of the moderator, the temperature of the moderator, and the excess reactivity. A value of 4.631×10^{-3} was used for the effective fraction

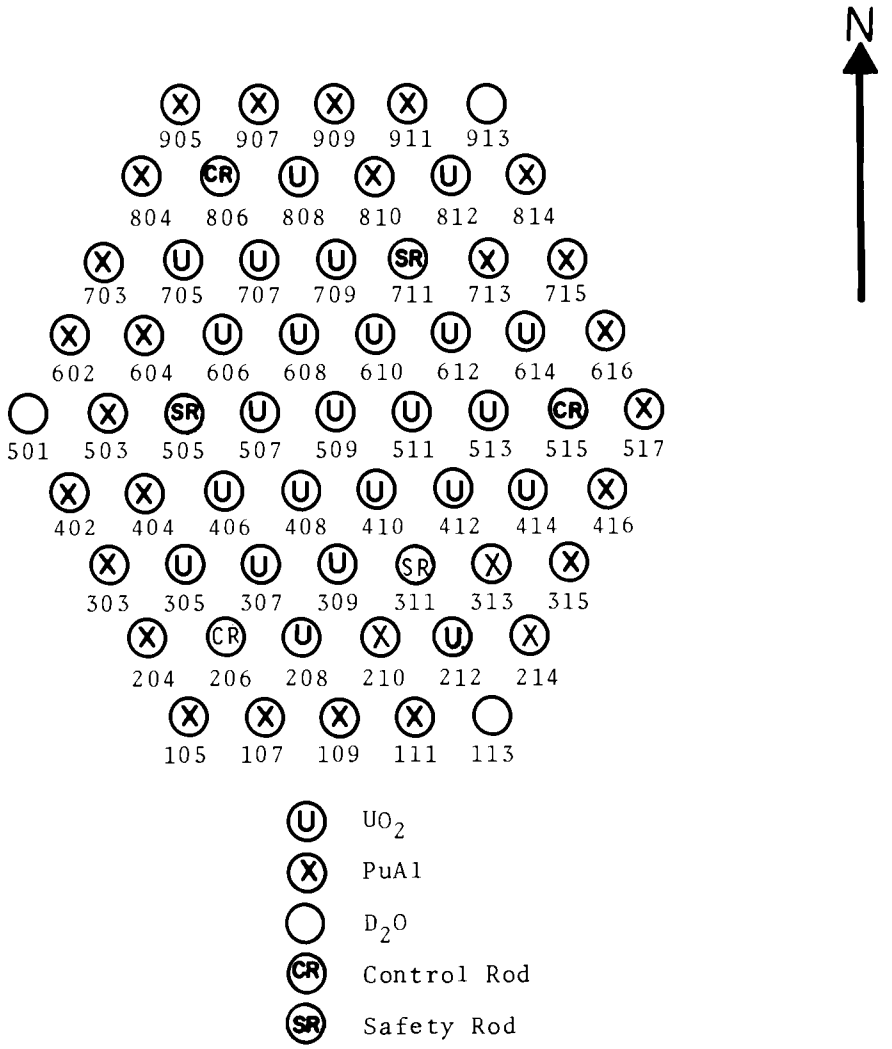


FIGURE 1. PRCF Loading Diagram: Loading No. E-9

of delayed neutrons, β_{eff}, which was used to obtain values of reactivity in terms of $\Delta k/k$. The uncertainties quoted in the last column of Table I are due only to errors in measuring doubling times.

Three safety rod channels, which consist of 3.50 in. OD, 3.115 in. ID aluminum thimbles containing air, were in all of the loadings described in this report. Diffusion-theory calculations predict a worth of 8.8 mk for replacing these three channels with D_2O.

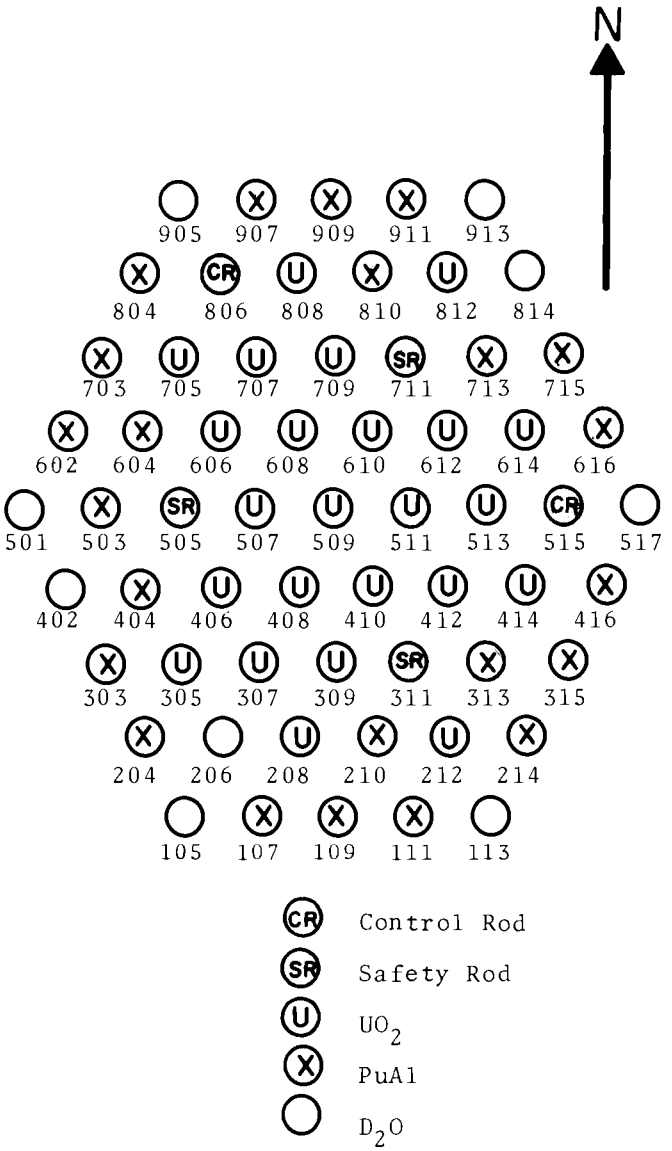


FIGURE 2. PRCF Loading Diagram: Loading No. E-12

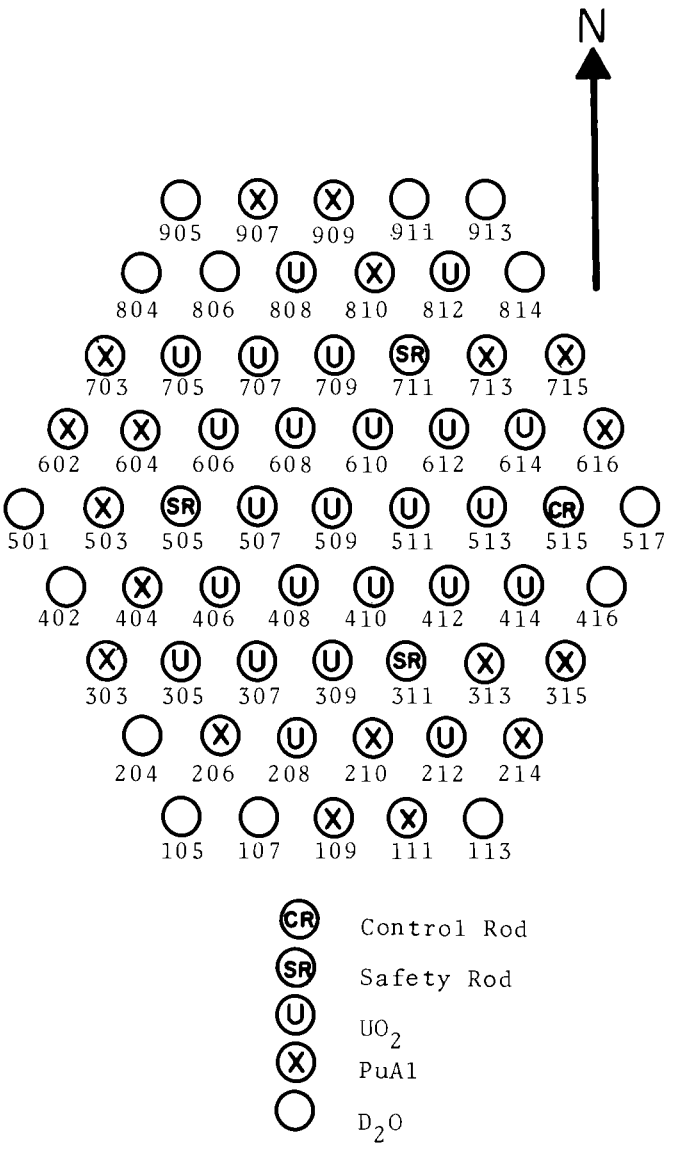


FIGURE 3. PRCF Loading Diagram: Loading No. E-14

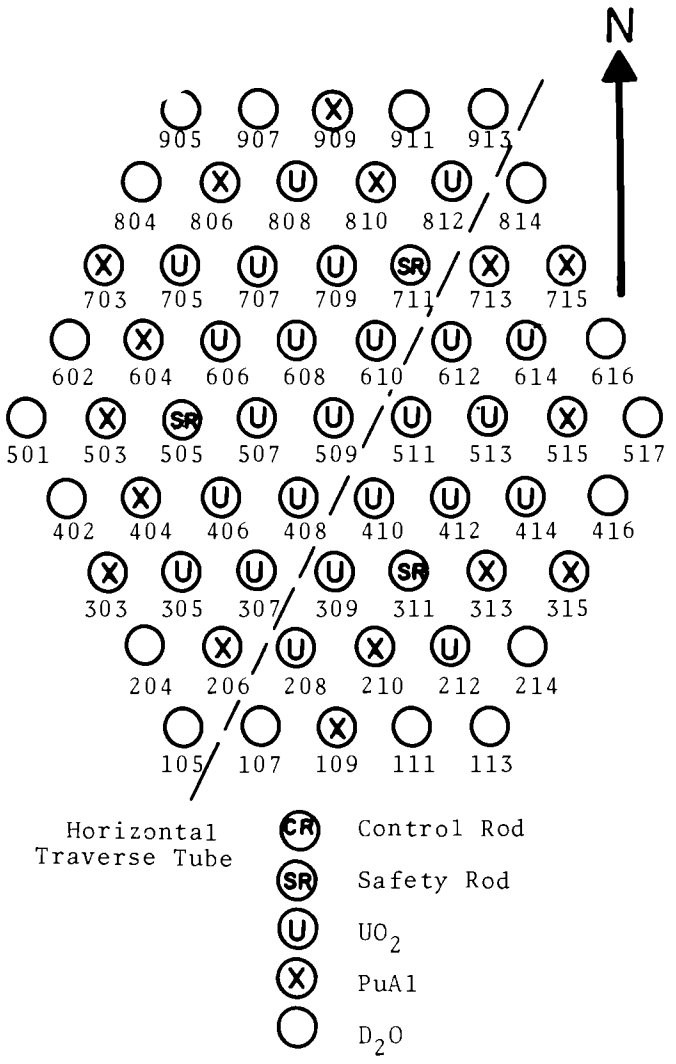


FIGURE 4. PRCF Loading Diagram: Loading No. E-17

REACTION RATES OF GOLD FOILS

The activation of gold foils was determined as a function of radial position in the control-rod-free reactor. This was done by irradiating gold foils, 0.500 in. in diameter and 0.005 in. thick, in a 3/4 in. OD aluminum tube which spans the reactor horizontally at a distance of 3 ft. 10 in. below the top of the top grid plate and crosses within 3.5 in. of the center of the reactor. Two of the foils were covered with 40 mils of cadmium.

The results of the traverse are compared in Figure 5 with a traverse that was taken in a loading that contained three control rods.[1] The two curves have been normalized at a point 4 in. SSW of center. The curve that was reproduced from Reference 1 shows a greater depression at the center which is due to an aluminum guide tube in the central cell, and a hump on the SSW side which is due to the presence of a safety rod void in a lattice position adjacent to the foils. In the present experiment this hump does not appear, because the safety rod positions have been rotated 60°. Instead there is

TABLE I. Critical Configurations

Loading Number	Positions of Control Rods No. 1	No. 2	No. 3	Moderator Height, in.	Moderator[b] Temp., °C	Reactivity, milli-k
E-9	open	open	closed	105.25	24.40	0.762 ± .001
E-12	removed	open	4.5 in. open	105.25	24.50	1.029 ± .002
E-14	removed	removed	open	105.25	25.08	0.831 ± .001
E-17	removed	removed	removed	100.00[b]	25.35	1.077 ± .004

[a] *Raising the moderator from 100.00 to 105.25 in. increases the reactivity by 1.62 ± .06 mk.*

[b] *The moderator temperature reactivity coefficient is -0.246 ± .005 mk/°C*

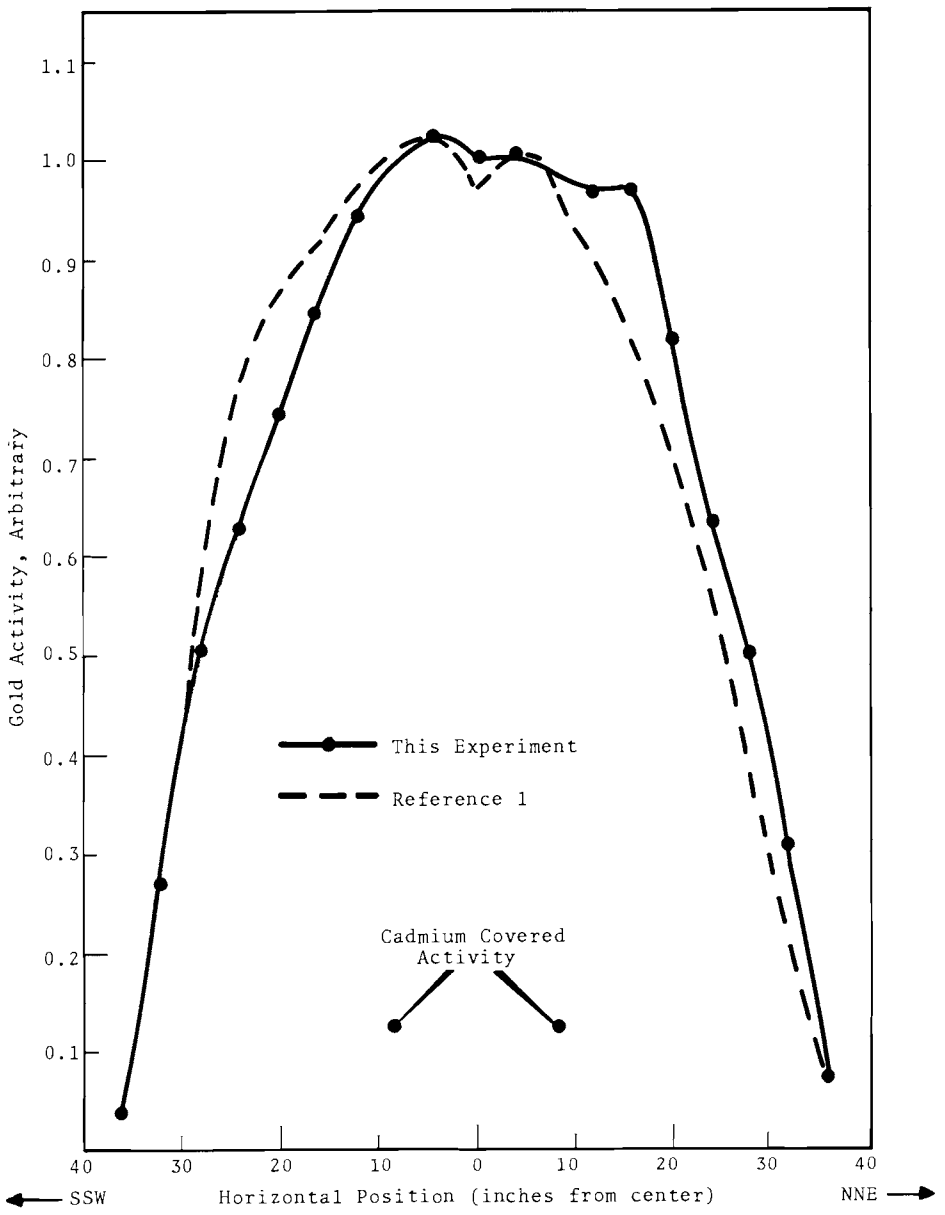


FIGURE 5. Radial Traverse with Gold Foils. The two curves have been normalized at a position 4 in. SSW of center.

now a hump on the NNE side, which now contains a safety rod void. Also, the hump on the NNE side is enhanced because a control rod has been removed from the NNE side.

The measured cadmium ratio for the 0.005 in. thick gold foils is 8.11 ± 0.08 for the point on the SSW side of center and 8.16 ± 0.08 for the point on the NNE side of center.

The Westcott epithermal index, r, was determined from the formula[4]

$$CdR(0) = \frac{g + rs}{r}\left[s + \frac{1}{K}\sqrt{\frac{T}{T_o}}\right]^{-1} \quad (1)$$

Here g, r, and s are the quantities that

lefine the effective cross section $\hat{\sigma}$ in the Westcott notation, i.e.,

$$\hat{\sigma} = \sigma_o(g + rs)$$

where σ_o is the cross section for neutrons with a velocity of 2200 m/sec. The K in Equation 1 is a cadmium transmission factor for thermal neutrons, T is the neutron temperature, and T_o is a reference temperature (293.6 °C). As obtained from Reference 4, the quantities g, s, and K are 1.005, $17.28\sqrt{\frac{T}{T_o}}$ and 2.2931 respectively. The CdR(0) in Equation 1 is the cadmium ratio for an infinitely dilute foil.

The CdR(0) was determined from the measured cadmium ratio CdR using the formula

$$\left[\frac{CdR(0)}{F} - 1\right] = Q\left[\frac{CdR}{F} - 1\right]. \qquad (3)$$

The Q-factor for a 5 mil gold foil was obtained from measurements by Jacks[5] and is 0.2288. The F is a correction factor which accounts for epithermal neutron absorption by the cadmium. Using a value of 1.02 for F and a value of 8.14 ± 0.08 for the measured cadmium ratio, we obtain 2.65 ± 0.02 for CdR(0). This, in turn, results in a value of 0.0338 ± 0.0004 for the quantity $r\sqrt{T/T_o}$ by using Equation 1.

A previous measurement of a gold cadmium ratio in a similar loading in the PRCF has been reported in Reference 1. The cadmium ratio of a 6 mil gold foil (40 mils cadmium) was found to be 8.2 ± 0.2 at a radius of 11.7 in. This results in a value of 0.0354 ± 0.0009 for the quantity $r\sqrt{T/T_o}$.

The quantity $r\sqrt{T/T_o}$ has also been deduced from lutetium activation data which were acquired in an experiment in the PRTR.[6] The PRTR data result in a value of 0.045 ± 0.004 for $r\sqrt{T/T_o}$ at a point in the moderator. This point is between UO_2 clusters and is as far as possible from all surrounding clusters.

The PRTR measurement results in a larger value of r than the PRCF measurements. The PRTR result is characteristic of the spectrum in the moderator; whereas, the PRCF result is characteristic of the spectrum inside the horizontal aluminum tube in which the foils were placed. Another difference between the two cases is that each fuel cluster in the PRTR is surrounded by an aluminum tube; whereas, the clusters in the PRCF are not. The volume ratio of D_2O-to-UO_2 is 11.8 in the PRTR and 13.6 in the PRCF.

REACTIVITY WORTH OF CONTROL RODS

Reactivity worths of incremental movements of control rod No. 3 were measured in loadings E-9, E-12, and E-14. (Figures 1 through 3 and Table I). Assuming that the shape of the integral worth curve for this control rod remains unchanged as the core size is varied, we can determine the worth of the rod (from shutter-closed to shutter-open) in each of these loadings. Calibrations of the PRCF control rods have been reported in Reference 1, where both differential and integral worth curves are presented. When the present measurements are compared with the results reported in Reference 1, we

find that the worth of control rod No. 3 from the shutter-closed position to the shutter-open position is 1.76, 1.53, and 1.31 mk in loadings E-9, E-12, and E-14 respectively.

After the control-rod-free configuration had been established, the control rods and their thimbles were reinstalled, one at a time, into the PRCF; and measurements were made to determine the change in reactivity produced by each successive addition. The control rods were in their "shutters open" condition.

The results are shown in Table II. Loadings E-25 and E-27 are identical to loadings E-12 and E-14, respectively, (Figures 2 and 3); and loading E-23 is shown in Figure 6. The negative worth of a control rod increased with each successive addition because the environment into which the control rod was placed was different for each loading. The subcritical method of determing reactivity changes from changes in multiplication is inherently less accurate than the supercritical method which involves measuring positive periods. This fact is reflected by the relatively large uncertainties in the control rod worths that were determined subcritically.

CALCULATIONS

The effective multiplication factor and the critical radius have been calculated by using the one-dimensional

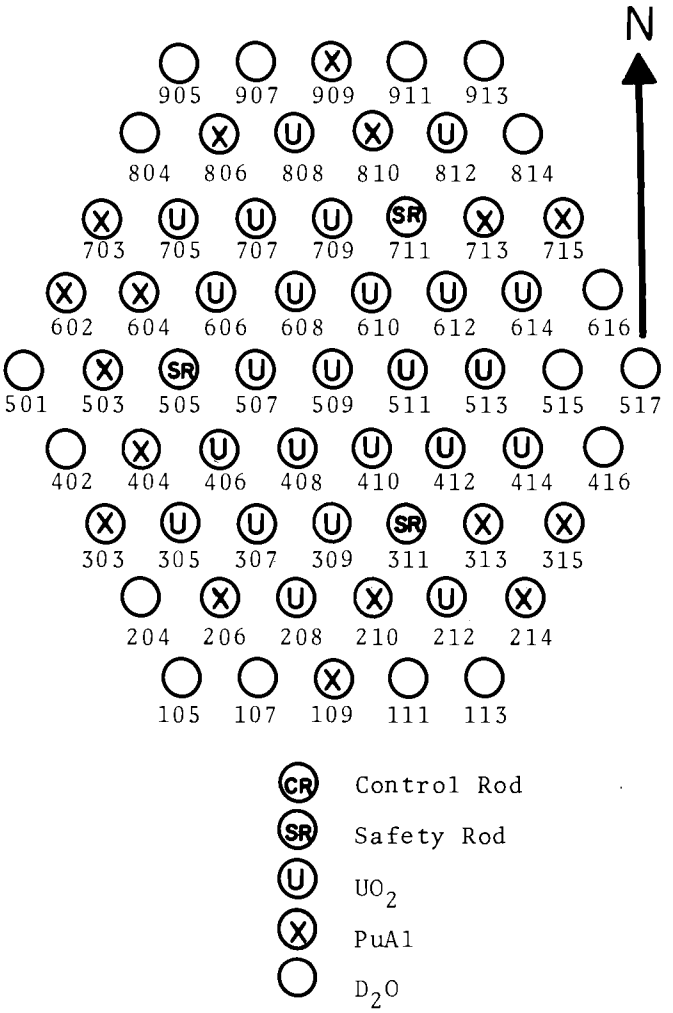


FIGURE 6. PRCF Loading Diagram: Loading No. E-23

TABLE II. Reactivities of PRCF Control Rods (Including Thimbles)

Initial Loading	Lattice[a] Position	Method of Measurement	Negative Worth, Milli-k
E-23	515	Positive Period	3.7 ± 0.1
E-25	806	Subcritical Multiplication	6.2 ± 0.6
E-27	206	Subcritical Multiplication	7.1 ± 0.5

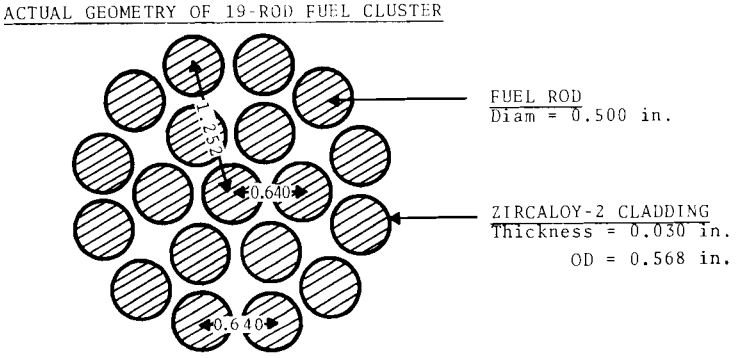
[a] *This is the lattice position into which the control rod was placed.*

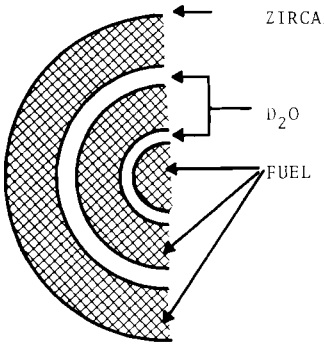
diffusion-theory code HFN[7] and assuming four groups of neutron energies as described in Table III. Cell average cross sections for the HFN calculations were generated with the codes THERMOS,[8] TEMPEST,[9] and HRG.[10] For THERMOS calculations involving clustered fuel elements, the fuel was assumed to be in three concentric rings which were separated by regions of cladding and D_2O (Figure 7). The scattering model assumed for D_2O was a modified Nelkin model[11] with isotropic scattering in the laboratory coordinate system. The technique used for spatial correction in the slowing down calculation was the same as described in Reference 12. Thermal cross sections for a safety rod cell with cadmium removed were obtained from a calculation[13] using the code TEMPEST. The volume fractions used in the calculations were 0.8267, 0.0358, and 0.1375, respectively, for D_2O, aluminum, and void. The regions used in the diffusion theory calculation are listed in Table IV.

TABLE III. Group Boundary Energies

Group	Lower Energy	Upper Energy
1	11.7 keV	10 MeV
2	2.38 eV	11.7 keV
3	0.683 eV	2.38 eV
4	0	0.683 eV

The calculated effective multiplication factor k_{eff} was 1.0068 for the





REGION NO.	MATERIAL	OUTER RADIUS, IN.
10	Clad	1.4133
9	Fuel	1.3715
8	Clad	1.0634
7	D_2O	1.0146
6	Clad	0.8152
5	Fuel	0.7763
4	Clad	0.4770
3	D_2O	0.4248
2	Clad	0.2840
1	Fuel	0.2500

MODEL OF 19-ROD FUEL CLUSTER

FIGURE 7. Geometry of 19-Rod Fuel Cluster

TABLE IV. Regions Used in Diffusion-Theory Calculation

Material	Outer Radius, cm	No. of Elementary Cells in Region
UO_2 Fuel	42.676	16
Safety Void	46.505	3
UO_2 Fuel	55.438	8
Pu-Al fuel	69.961	16
D_2O	92.075	(reflector)
Al + Cd	92.126	(reactor vessel wall)

just critical condition of the loading represented by Figure 4. The calculated critical radius was 68.78 cm; whereas, the "measured" critical radius was 69.96 cm. The "measured" critical radius, R, was defined as $R = \sqrt{\frac{NA}{\pi}}$, where N is the number of lattice positions occupied by fuel or safety rod voids, and A is the area of a unit cell. The calculations were performed assuming a temperature of 20 °C and a moderator height of 105.25 in. The calculated results have been corrected to agree with the experimental temperature (25.35 °C) and moderator height (98.15 in.). A temperature coefficient of -0.246 mk/°C[14] was used to correct for the difference in temperature, and published moderator reactivity worth curves[15] were used to correct for the difference in moderator height.

Relative reaction rates of bare gold foils were obtained from the calculated fluxes. The relative reaction rate, R(r), was defined as

$$R(r) = \frac{\phi_{th,c}(r) + k\phi_{F,c}(r)}{\phi_{th,c}(0) + k\phi_{F,c}(0)} \qquad (4)$$

where

$$k = C\left\{\frac{D_{th}}{\frac{\sqrt{\pi}}{2}\sigma_o f}\left(RI_{ec} + \frac{RI_{es}}{D_{es}}\right)\right\} \qquad (5)$$

The $\phi_{th,c}$ is the thermal flux (0 to 0.683 eV) as calculated with the code HFN, and $\phi_{F,c}$ is the sum of the fluxes of the nonthermal groups (groups 1, 2 and 3 in Table III) as calculated with HFN. The other parameters are defined as follows:

σ_o = microscopic activation cross section at 2200 m/sec

f = non-1/v correction factor

D_{th} = average foil disadvantage factor for thermal Maxwelliam neutrons

D_{es} = average foil disadvantage factor for epithermal-subcadmium neutrons

RI_{ec} = effective epicadmium resonance integral

RI_{es} = epithermal-subcadmium resonance integral.

The constant C was determined experimentally, and it relates the ratio, ϕ_{th}/ϕ_F, of the actual thermal and epithermal fluxes to the ratio calculated with HFN. The calculated ratio, $\phi_{th,c}/\phi_{F,c}$, is 1.624 at r = 8.0 in. Thus, the constant C is given by

$$C = 1.624\,\frac{\phi_{th}(8.0)}{\phi_F(8.0)} \qquad (6)$$

or

$$C = 1.624\,\frac{\frac{\sqrt{\pi}}{2}\sigma_o f}{RI_{ec} D_{th}}\left[\frac{CdR}{1.02} - 1\right]^{-1} \qquad (7)$$

where CdR is the measured gold cadmium ratio at r = 8.0 in.

Inserting Equation (7) into Equation (5), and using the measured cadmium ratio, 8.14, we have

$$k = 0.233\left[1 + \frac{RI_{es}}{D_{es} RI_{ec}}\right] = 0.265 \qquad (8)$$

The values used for D_{es}[16], RI_{es}[16], and RI_{ec}[17] are 1.0412, 52 barns,

and 354 barns, respectively. The relative reaction rate is, thus, given by

$$R(r) = \frac{\phi_{th,c}(r) + 0.265\ \phi_{F,c}(r)}{\phi_{th,c}(o) + 0.265\ \phi_{F,c}(o)} \quad (9)$$

The R(r) is shown as the solid curve in Figure 8, where it is compared with the observed gold activation distribution. The calculated distribution agrees more closely with the NNE traverse than with the SSW traverse because the geometry used in the calculation more closely resembles the geometry on the NNE side.

CONCLUSIONS

It is difficult to accurately represent discrete control rods in a one-dimensional diffusion theory calculation. To assist in the evaluation of calculational methods a control-rod-free critical configuration was assembled in the D_2O-moderated PRCF.

A calculation with the diffusion theory code HFN, using cell-average cross sections generated with the codes THERMOS, TEMPEST, AND HRG, predicts the effective multiplication factor to within 0.7% of the measured value for the control-rod-free loading of UO_2 and Pu-Al clusters.

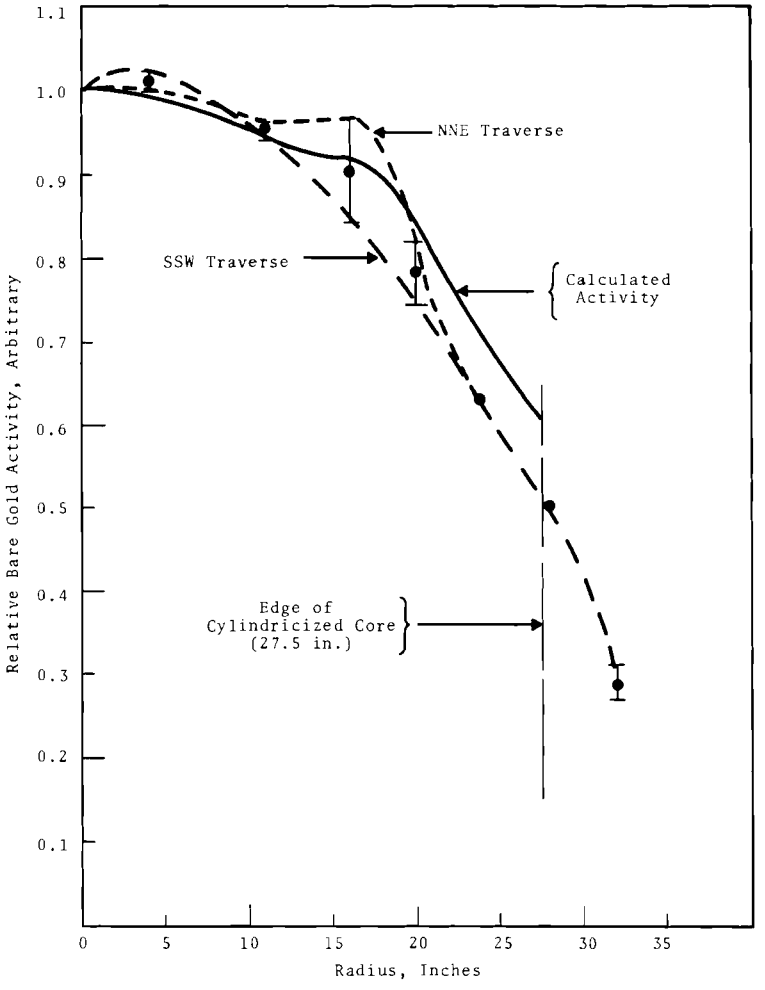


FIGURE 8. Comparison Between Calculated and Observed Gold Activity (The Tips of the Error Flags Define the NNE and SSW Experimental Traverses. The Solid Line is the Calculated Activity from HFN. The Curves Have Been Normalized at the Center.)

The calculational scheme of THERMOS, HRG, TEMPEST, and HFN has been used to calculate the effective multiplication factor of a Pu-Al-D_2O loading[18] the calculated k_{eff} is ∿4% high. The same calculational method has been used to calculate infinite multiplication factors for UO_2-D_2O systems;[19] the calculated k_∞ are consistently ∿3% low. Thus, it appears that the good agreement that we obtain between the calculated and measured k_{eff} for our two-zone loading may be the result of compensating errors.

The calculated gold activity is considerably greater than the measured activity at radii greater than ∿20 in. This discrepancy may be caused in part by the failure of diffusion theory to adequately represent events near the core-reflector boundary. Another reason for the discrepancy may be because the calculational method consistently overestimates the resonance absorption in uranium cells.[19] Thus, the calculated neutron density in the inner (UO_2) zone is expected to be low.

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