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MODERATOR REACTIVITY COEFFICIENTS
FOR THE H₂O MODERATED,
1.8 WT% Pu-Al LOADING
IN THE PRCF

V. O. Uotinen, A. L. Pitner, W. P. Stinson

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By

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INTRODUCTION

Reactivity worths of moderator level changes have been measured in the Plutonium Recycle Critical Facility (PRCF) for a loading of 1.82 wt% Pu-Al fuel moderated by H₂O. From these measurements the migration area of the core can be deduced. For an H₂O moderated loading, the main contribution to the migration area comes from the slowing down area for the fast group of neutrons. Therefore, a comparison between experimental and calculational migration areas is a measure of the correctness of methods of calculating fast group parameters. The migration area of the core is determined from the variation of the moderator coefficient of reactivity with moderator height. A value of 42 ± 5 cm² is obtained for the migration area of this reactor loading. The value obtained from a diffusion theory calculation using four energy groups is 54 cm².

DESCRIPTION OF EXPERIMENT

The fuel was in the form of rods with 0.500 ± 0.001 in. diameters and 43.83 in. lengths. This was fuel originally fabricated for the PRTR and subsequently cut in half. These rods were sealed in Zircaloy-2 tubes of 0.505 ± 0.001 in. ID with 0.030 ± 0.003 in. thick walls. The end caps were also of Zircaloy but of various sizes and shapes. The average weight

of the top end caps and associated tubing was 21.6 g, and that of the bottom caps 12.4 g.

The average plutonium content was 7.12 g per rod. The amount of Pu-240 in the plutonium varied from 4.75% to 6.10%. The rods were loaded in the reactor in a three-zone configuration. Rods with highest Pu-240 content were placed in a zone of minimum worth⁽¹⁾ and rods with lowest Pu-240 were placed in a zone of highest worth. An average composition for the plutonium by weight is 93.97% Pu-239, 5.58% Pu-240, 0.44% Pu-241, and 0.014% Pu-242.

The lattice was hexagonal in shape with a spacing of 0.800 ± 0.001 in. This corresponds to a moderator to fuel rod volume ratio of 1.203, and H/Pu atom ratio of 810. The fuel rods were positioned by three lucite lattice plates, the uppermost being situated 5.5 in. below the top of the fuel.

The safety rods were of the "fuel-follower" type. A fuel rod is attached to the bottom of each safety rod, so that as the safety rods are withdrawn, they are immediately replaced with fuel. These fuel rods were 1.50 wt% PuO₂-UO₂ with a length of 48.5 in. The safety sheets in their withdrawn positions are 6 in. above the top of the fuel, so with the safety rods and safety sheets out, the system is essentially poison free with no voids.

A moderator coefficient of reactivity was found by measuring positive reactor periods at each of two slightly different moderator levels. The difference in excess reactivity at these levels divided by the incremental change in moderator height gives the sensitivity or moderator coefficient of reactivity at the midpoint between the moderator levels.

As the moderator was lowered during the experiment, more fuel rods were added to compensate for the reduction in reactivity and keep the reactor supercritical at each moderator level.

ANALYSIS OF DATA

The sensitivities measured for moderator levels above the top of the fuel are shown in Figure 1. The curve is a visual fit to the experimental values. The discontinuity near the top of the fuel is probably due to the different scattering properties of the region containing the Zircaloy end-caps.

To find the reactivity worth of any change in height of moderator, the sensitivity, S , is integrated over that interval.

$$\Delta\rho = \frac{\Delta k}{k} \bigg|_{H_1}^{H_2} = \int_{H_1}^{H_2} S \, dH \quad (1)$$

This is just the area under the curve of sensitivity versus moderator height in that interval. The area under the curve in Figure 1 from 0 to 6 in. above the top of the fuel gives a value of 91.5ϕ for the worth of the top reflector. When the individual incremental reactivity changes are summed this same worth is found to be $88 \pm 1\phi$.

The sensitivities measured for moderator levels below the top of the fuel are shown in Figure 2. The dashed lines demonstrate the expected effect of the lucite lattice plate. Since lucite has much the same moderating properties as H_2O , there is essentially no reactivity change as the moderator is lowered through this region. Once the moderator drops below the template, however, this total moderating volume is effectively lost, resulting in a large reactivity decrease at this point.

According to multigroup diffusion theory, the effective multiplication factor for a large light water moderated reactor can be expressed as⁽²⁾

$$k_{eff} = \frac{k_{\infty}}{1 + M^2 B^2} \quad (2)$$

FIGURE 1

Moderator Level Reactivity Coefficients
The curve is a visual fit to the experimental points.

FIGURE 2

Moderator Level Reactivity Coefficients

The solid curve is from Equation (7). The dashed lines demonstrate the distortion caused by the lattice plate.

where M^2 is the migration area and B^2 is the buckling. Substituting this relationship into the equation defining the sensitivity results in the expression

$$S \equiv \frac{1}{k_{\text{eff}}} \frac{\partial k_{\text{eff}}}{\partial H} = \left(\frac{2\pi^2 M^2}{1 + M^2 B^2} \right) \frac{1}{H^3} \quad (3)$$

where H is the effective height of the reactor. This equation can be modified to give

$$S^{-1/3} = \left(\frac{2\pi^2 M^2}{1 + M^2 B^2} \right)^{-1/3} (H_p + \lambda) \quad (4)$$

where the effective height has been expressed explicitly as the sum of the physical height of the moderated fuel, H_p , and a constant, λ , which is the sum of the extrapolation distances at the top and bottom of the core.

If the term in parentheses in Equations (3) and (4) is constant, either or both of these equations can be used to determine the migration area. By the method of Equation (3), the migration area is determined from the slope of the line, S , versus H^{-3} . By the method of Equation (4), it is determined from the slope of the line $S^{-1/3}$ versus H_p .

The term in parentheses in Equations (3) and (4) is constant if the buckling remains constant as the moderator is lowered. This is in fact the case. The axial buckling increases as the moderator is lowered but the total buckling remains constant because of a compensating decrease in the radial buckling. This decrease in radial buckling is effected by the addition of fuel rods as necessary to keep the reactor critical at the lower moderator heights.

The buckling of the reactor is given by the formula

$$B^2 = \left(\frac{2.405}{R + \lambda} \right)^2 + \left(\frac{\pi}{H + 2\lambda} \right)^2 \quad (5)$$

where λ , the extrapolation distance, is assumed to be the same axially and radially. The radius, R , is found from the expression

$$R = \ell \sqrt{\frac{N\sqrt{3}}{2\pi}} \quad (6)$$

where ℓ is the lattice pitch and N is the number of fuel rods required to attain criticality with an effectively infinite reflector surrounding the core. The buckling calculated in this manner is $63.19 \pm 0.29 \text{ m}^{-2}$.

The analysis was performed using both Equation (3) and Equation (4). When Equation (3) is used, one has to know the effective height and, hence, the extrapolation distances. The top extrapolation distance for moderator levels below the top of the core was neglected because it was expected to be small owing to the short transport mean free path of the core. The bottom extrapolation distance was determined in a subcritical experiment⁽³⁾ and was found to be $3.25 \pm 0.03 \text{ in.}$ To check the validity of this value a cosine function was fitted to Lu-176m subcadmium activation data obtained from irradiated lutetium foils that had been positioned along the axis of the reactor. This analysis results in a bottom extrapolation distance of $3.48 \pm 0.55 \text{ in.}$ When Equation (4) is used in the analysis, a value for the extrapolation distance is not needed since $S^{-1/3}$ is directly proportional to $H\rho$.

Using the method of Equation (3), the experimental sensitivities were plotted against H^{-3} where H is the length of moderated fuel plus 3.25 in. A straight line was fitted to these points by the method of least squares,

weighting the points inversely as the squares of their errors. The resulting equation is

$$S = (54.8 \pm 0.9) + (48.0 \pm 5.0)10^5 (H^{-3} - 1.223 \times 10^{-5}) \quad (7)$$

where S is in $\phi/\text{in.}$ and H is in inches.

Using the method of Equation (4) a straight line was fitted to a plot of $S^{-1/3}$ versus H_p . The equation obtained is

$$S^{-1/3} = (0.2650 \pm 0.0015) + (6.43 \pm 0.69)10^{-3} (H_p - 40.36) \quad (8)$$

where S is in $\phi/\text{in.}$ and H_p is in inches.

Equations (7) and (8) yield identical results for the sensitivity as a function of moderator height. The curve that is generated by these equations is shown in Figure 2.

The worth of any change in height of moderator is found by integrating S between the initial and final heights. Integration of Equation (7) results in the expression

$$\begin{aligned} \frac{\Delta k}{k} \bigg|_{H_1}^{H_2} = & (54.8 \pm 0.9)(H_2 - H_1) - (24.0 \pm 2.5)10^5 \left[\frac{1}{H_2^2} - \frac{1}{H_1^2} \right. \\ & \left. + 2.446 \times 10^{-5} (H_2 - H_1) \right] \end{aligned} \quad (9)$$

which gives the reactivity change in cents associated with any change in moderator height, $H_2 - H_1$. Equation (9) is valid in the region from the top of the fuel to 8 in. below the top of the fuel.

Figure 3 shows the accumulative loss in reactivity as the moderator is lowered from 6 in. above to 8 in. below the top of the fuel. The portion of the curve below the top of the fuel is calculated from Equation (9) and assumes that the template has been replaced with H_2O .

FIGURE 3

Reactivity Loss as a Function of Moderator Height
 The reactivity loss refers to that from full moderator height. The portion of the curve below the top of the fuel is from Equation (9).
 The effect of the template has been neglected.

ERRORS

The primary sources of error in the sensitivities were uncertainties in the measurement of positive periods and moderator heights. The period measurements contained an uncertainty of $\sim \pm 0.2 \phi$. The moderator height, H , is expected to have an uncertainty of ± 0.010 in. Subsequent analysis of the scattering of the experimental points about the best fitting straight line indicated that the assumption of ± 0.010 in. was a good approximation for the uncertainty in H .

MIGRATION AREA

From the slope of Equation (7), the migration area is found to be $42 \pm 5 \text{ cm}^2$. The value obtained from the slope of Equation (8) is $31 \pm 12 \text{ cm}^2$. Analysis of the latter equation results in an unrealistic value and large error (0.48 ± 4.45 in.) for the extrapolation distance. If the curve is forced to give a more realistic value for the extrapolation distance (3.25 in.) by adding a data point at $H = -3.25$ in., the resulting migration area is 38 cm^2 . This is within the statistical uncertainty of the value obtained from Equation (7). It is felt that the best experimental value for the migration area is that obtained from the analysis that results in Equation (7), $42 \pm 5 \text{ cm}^2$. The other method of analysis would require additional data points to yield a comparable migration area and a realistic extrapolation distance.

The migration area has also been calculated using four-group diffusion-theory. The sources for the nuclear parameters are described in Reference (4). Diffusion coefficients and slowing down cross sections for the homogenized core and the reflector were calculated⁽⁵⁾ for each of the four energy groups. When these are weighted by flux and volume they result in the parameters listed in Table I.

TABLE I

GROUP CONSTANTS FOR CALCULATION OF MIGRATION AREA

<u>Energy Group (i)</u>	<u>Energy Range</u>	<u>D_i (cm)</u>	<u>Σ_i (cm⁻¹)</u>	<u>D_i/Σ_i (cm²)</u>
1	10 MeV to 11.7 keV	1.7720	4.6902 x 10 ⁻²	37.78
2	11.7 keV to 2.38 eV	0.8756	9.0241 x 10 ⁻²	9.70
3	2.38 eV to 0.683 eV	0.8519	4.5534 x 10 ⁻¹	1.87
4	0.683 eV to 0.0 eV	0.2133	4.9863 x 10 ⁻²	4.28

The Σ_1 , Σ_2 and Σ_3 are macroscopic cross sections for the removal of neutrons from one energy group either by absorption within the group or by slowing down to lower energy groups. The Σ_4 is the thermal macroscopic absorption cross section, and the D_i are diffusion coefficients. The migration area is the sum of the D_i/Σ_i . The result is a value of 53.63 cm².

The calculated value is not within the uncertainty of the experimental value. The results from a PuO₂-UO₂-H₂O core in the FRCF indicate a similar discrepancy.⁽²⁾ In both cases the calculated value is higher than the experimental value by approximately 10 cm².

If the migration area that is calculated is indeed the same physical quantity as is measured, then the difference between the two should be attributable to the nuclear parameters used in the calculation. Some of the D_i may be high and some of the Σ_i may be low. The greatest contribution to the calculated migration area comes from the ratio D_i/Σ_i for the fast group (group 1). The difference between the calculated and measured migration areas could be attributed entirely to inaccuracies in the fast group constants, since these are more likely to contain inaccuracies than the parameters of other energy groups.

For the present experiment the difference could be explained if the ratio D_1/Σ_1 were high by $\sim 30\%$. The D_1 and Σ_1 are not independent quantities. The diffusion coefficient is defined by

$$D_i = \frac{1}{3\Sigma_{tr_i}} \quad (10)$$

where Σ_{tr_i} is the total macroscopic transport cross section for the group.

The removal cross section is defined by

$$\Sigma_i = \Sigma_{ai} + \Sigma_{out_i} \quad (11)$$

where Σ_a is the macroscopic cross section for absorption and Σ_{out} is the macroscopic cross section for slowing down to lower energy groups. By far the largest contribution to both Σ_{tr_1} and Σ_1 is from the scattering cross section Σ_{s_1} for hydrogen. Hence, if Σ_{tr_1} and Σ_1 are in error, one would expect that this is because Σ_{s_1} for hydrogen is in error. The ratio D_1/Σ_1 would be high by 30% if Σ_{s_1} for hydrogen were low by 20%. This would account for the difference between the measured and calculated migration areas. However, while increasing the scattering cross section for hydrogen by 20% would lead to a calculated migration area that is in agreement with experiment, it would upset some correlations between other parameters. For example, the calculated effective multiplication factor, which is presently about 2% higher than the experimental value, would be increased further by 5%; also, the calculated age to thermal in H_2O , which is presently in good agreement with experiment, would be reduced by some 20%.

The migration area that is calculated may not be the same physical quantity which is deduced from the measurement since the calculational model may not be compatible with the model used in the analysis of the experimental data. Additional experiments and calculations are needed

to help resolve the difference between calculated and measured migration areas. One calculation that might help resolve this difference is a two-dimensional diffusion theory calculation of reactivity worths of moderator level changes. This would be a direct calculation of the quantities that were actually measured in the experiment.

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