**REACTIVITY WORTH OF A CENTRAL
SAFETY ROD WITH AND WITHOUT
AN INTERNAL SCATTERER**

V. O. UOTINEN AND A. L. PITNER

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WITH AND WITHOUT AN INTERNAL SCATTERER

By

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INTRODUCTION

An experiment has been performed in the D₂O-moderated Plutonium Recycle Critical Facility (PRCF)⁽¹⁾ to determine the increase in the negative reactivity worth of a hollow cadmium safety rod when a scattering material (Lucite) is placed inside the safety rod. The experiment was conducted to investigate the feasibility of increasing the worth of the PRCF safety system for special purposes, and to evaluate calculational methods of determining the worth of safety rods with internal scattering. The PRCF was loaded with a two-zone configuration of 1.8 wt% Pu-Al⁽²⁾ and natural UO₂,⁽³⁾ and the safety rod was located in a central fuel channel.

SUMMARY AND CONCLUSIONS

The worth of the central safety rod was measured subcritically to be 40.7 ± 0.6 mk ($8.78 \pm 0.13\%$). The negative worth increased by 9.2% when Lucite filled the interior of the safety rod. The worth of the safety rod, as determined from a diffusion theory calculation using four energy groups, is 40.4 mk. The calculated worth increased by 15.6% when Lucite was added to the interior.

The rather small effect that the internal scatterer had on the worth of a safety rod indicates that for the PRCF loading, as studied, this is not a practical method of increasing the worth of the safety system. However, the effect of adding Lucite would be greater in a loading in which the ratio of epithermal neutrons to subthermal neutrons is greater than in this core.

Effective multiplication factors, calculated for the present core using the series of computer codes HRG, THERMOS, TEMPEST, AND HFN, are ~ 1 higher than experimental values when the thermal absorption cross section of the control rod region is normalized so that the worth of the control rod region agrees with an experimental estimate of its worth. The worth of a central safety rod, as calculated with these codes, agrees well with the measured worth; however, the decrease in reactivity produced by adding Lucite to the interior of the safety rod is overestimated.

DISCUSSION

DESCRIPTION OF EXPERIMENT

The core loading consisted of an inner zone of natural UO_2 fuel elements surrounded by a zone of 1.8 wt% Pu-Al fuel elements in which the isotopic composition of plutonium was 93.55 wt% ^{239}Pu , 6.00 wt% ^{240}Pu , 0.45 wt% ^{241}Pu , and <0.01 wt% ^{242}Pu . Each fuel element was a cluster of 19 fuel rods. Each rod was 0.500 in. in diameter, 88 in. in length, and surrounded by a 0.030 in. thick Zircaloy jacket. The rods of a cluster were separated by a 0.072 in. wire wrap. The average plutonium content in the Pu-Al rods was 14.16 g per rod, and the average uranium content in the UO_2 rods was 2.55 kg per rod. The fuel clusters were arranged in a hexagonal lattice with an 8 in. pitch. The moderator height was 105.25 in. during the reactivity measurements and the thicknesses of the D_2O reflectors at the top and bottom of the core were 8.34 and 9.04 in., respectively.

A safety rod, consisting of a 2.695 in. OD, 2.303 in. ID, and 85 in. long aluminum cylinder coated with a 0.025 in. layer of cadmium, was placed in an aluminum thimble in the center of the PRCF (Figure 1). The aluminum thimble had an outer diameter of 3.47 in. and a wall thickness of 0.18 in.

FIGURE 1. The Subcritical Loading in Which the Worth of a Central Safety Rod Was Measured

The worth of this safety rod was determined from sub-critical multiplication data which were obtained from three BF_3 chambers positioned in the radial reflector. The count rate was measured with and without the safety rod in the thimble, and the worth was calculated using the equation

$$\Delta k_{\text{eff}} = A \left(\frac{N_1}{N_2} - 1 \right) (1 - k_{\text{eff}_1}) \quad (1)$$

In Equation 1, Δk_{eff} is the worth of the safety rod, and N_2 and N_1 , respectively, are the count rates with and without the safety rod in the thimble. The k_{eff_1} is the effective multiplication factor of the reactor in the absence of the safety rod, and A is an empirically determined constant. The constant, A , was determined for each chamber by measuring multiplications before and after inserting into the reactor (at a radius of 16 in.) a safety rod of known worth, and using Equation (1).

The loading was changed (Figure 2) so that the reactor could be taken supercritical with the safety rod in the center. Measurements of positive periods were made to determine the decrease in reactivity caused by the addition of Lucite to the interior of the safety rod. A Lucite sleeve 2.240 in. OD, 1.550 in. ID, and 84 in. long, was placed in the safety rod. Subsequently, a Lucite rod 1.510 in. in diameter and 75 in. long was placed inside the Lucite sleeve. The Lucite rod rested on a guide and was flush with the Lucite sleeve at the top (Figure 3). A measurement was also made of the reactivity worth of a stainless steel rod to simulate the lead screw of a regular PRCF safety rod. This simulated lead screw of 0.875 in. diam penetrated 7.7 in. below the top of the cadmium section of the safety rod.

FIGURE 2. The Supercritical Loading in Which the Worth of Lucite in the Central Safety Rod Was Measured

FIGURE 3. *The Arrangement of the Lucite Inside the Safety Rod*

EXPERIMENTAL RESULTS

Flux Distribution

A radial distribution of gold activation was determined by irradiating gold foils, 1/2 in. diam 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. from the top of the top grid plate, and crosses within 3.5 in. of the center of the reactor. The presence of the safety rod in the center of the reactor greatly depressed the thermal flux in this region, as shown in Figure 4. The asymmetry of the flux distribution is due to the nonsymmetrical loading of the core (Figure 2). The flux in the southwest region is depressed by a control rod there which leaves poison in the reactor even in its withdrawn position. The flux in the northeast region is enhanced by the presence of an extra Pu-Al fuel element.

Control Rod Calibration

With such an abnormal flux distribution, it was necessary to recalibrate the control rod (No. 3) used to make reactivity adjustments during this experiment. The calibration was done by supercritical period measurements with the reactor loaded as shown in Figure 2. The results are shown in Table I.

TABLE I. *Control Rod No. 3 Calibration*

<u>Inches Out</u>	<u>Differential Worth, mk</u>	<u>Integral Worth, mk</u>
6.0775 (out)		0.000
5.0000	0.389 $\pm$ 0.007	0.389 $\pm$ 0.007
4.5000	0.206 $\pm$ 0.008	0.595 $\pm$ 0.011
3.5000	0.377 $\pm$ 0.008	0.972 $\pm$ 0.013
2.5000	0.346 $\pm$ 0.008	1.318 $\pm$ 0.016
1.5000	0.297 $\pm$ 0.008	1.615 $\pm$ 0.018
0.0000	0.227 $\pm$ 0.008	1.842 $\pm$ 0.019

* The HTM is the tube in which the traverse was obtained. It passes within 3.5 in. of the center of the reactor.

FIGURE 4. Radial Gold Foil Traverse with a Safety Rod in the Center of the PRCF. The curves are visual fits to the points. The uncertainties in the points are less in magnitude than the symbols representing the points.

Reactivity Measurements

The negative worth of the safety rod in the center of the reactor, as determined from subcritical multiplication measurements, was 40.7 ± 0.6 mk ($8.78 \pm 0.13\%$).

Addition of the Lucite sleeve to the safety rod increased the negative worth of the safety rod 2.36 ± 0.02 mk ($51.0 \pm 0.4\%$). Placing the Lucite rod inside the sleeve increased the negative worth by an additional 1.40 ± 0.01 mk ($29.2 \pm 0.2\%$). The total effect, then, of replacing the internal void of the safety rod with Lucite, is a 9.2% enhancement of its negative worth.

The simulated lead screw was worth -0.040 ± 0.004 mk ($-0.9 \pm 0.1\%$). The net contribution of the Lucite sleeve to the worth of a PRCF safety rod (with lead screw present) is 2.34 ± 0.02 mk ($50.5 \pm 0.4\%$) or an increase of 5.7%.

Calculation of Safety Rod Worth

The worth of the safety rod, with and without Lucite, was calculated using a system of computer codes that has been used successfully to calculate critical masses and effective multiplication constants for a number of reactor loadings.^(4,5) The system of codes consists of HRG⁽⁶⁾ for determining fast cross sections; THERMOS⁽⁷⁾ for thermal cross sections; TEMPEST⁽⁸⁾ for the thermal diffusion coefficient; and HFN⁽⁹⁾ for a one-dimensional 4-group diffusion-theory calculation of the neutron leakage from the reactor. The lower energy boundaries of the groups are 11.7 keV, 2.38 eV, 0.683 eV and zero.

The combination of codes HRG, THERMOS, and TEMPEST was used to generate cell average cross sections for each of four kinds of elementary cells: a Pu-Al cluster, a UO₂ cluster, the central safety rod, and a D₂O cell. All microscopic cross sections are from the BNW Master Library.⁽¹⁰⁾ For THERMOS cell calculations involving the clustered fuel elements, the fuel

Thermal cross sections for a cell containing a safety rod void were obtained from a calculation⁽¹³⁾ using the code TEMPEST. The volume fractions used in the calculation for D₂O, aluminum, and void, were 0.8267, 0.0358, and 0.1375, respectively.

Thermal cross sections for a cell containing a control rod were calculated⁽¹³⁾ with the TEMPEST code. The volume fractions of D₂O, aluminum, and cadmium, were 0.9652, 0.0205, and 0.0017, respectively. For the reactor calculation, the thermal absorption cross section of the control rod region was reduced from a value of 0.124 cm⁻¹ to 0.00280 cm⁻¹, so that replacing the control rod region with D₂O increased the calculated k_{eff} by 2.3%, which is an experimental estimate of their worth.

The technique used for spatial correction in the slowing down calculations was the same as described in Reference 14.

Homogenized cross sections, generated with HRG, THERMOS, and/or TEMPEST, were used in the diffusion-theory code HFN to calculate the effective multiplication factor. The regions used in the diffusion theory calculations are described in Table III. The change in k_{eff} when D₂O replaces the safety rod cell which contains Lucite is 48.2 mk, and the change in k_{eff} when D₂O replaces the safety rod cell without Lucite is 41.9 mk. The safety rod cell considered in the calculations includes the thimble into which the cadmium-coated safety rod is inserted. To compare the calculated results with measured results we must subtract from the calculated results the Δk_{eff} produced when the thimble is replaced by D₂O, 1.5 mk.⁽¹⁵⁾ When this is done, the calculated worth of the safety rod with no Lucite is 40.4 mk, and the calculated worth of the safety rod containing Lucite is 46.7 mk. The calculated effect of filling the interior of the safety rod with Lucite is an increase of 15.6% in the negative worth of the safety rod.

TABLE III. *Description of Regions Used in Diffusion Theory Calculations*

<u>Material</u>	<u>Outer Radius, cm</u>	<u>Number of Elementary Cells in Region</u>
Central Test Cell ^(a)	10.669	1
UO ₂ Fuel	42.676	15
Safety Rods ^(b)	46.505	3
UO ₂ Fuel	53.345	6
Pu-Al Fuel	59.403	6
UO ₂ Fuel	61.289	2
Control Rods ^(c)	64.014	3
Pu-Al Fuel	83.328	25
D ₂ O	92.075	(reflector)
Al + Cd	92.126	(wall of reactor vessel)

(a) *Three cases were considered, in which the central cell contained 1) a safety rod without Lucite, 2) a safety rod with Lucite, or 3) D₂O; the calculated k_{eff} for these three cases are 0.96951, 0.97583, and 1.01769, respectively. The measured k_{eff} corresponding to Case 3 is 1.0055.*

(b) *The safety rod region was calculated to be worth +8.8 mk when replaced with D₂O.*

(c) *The control rod region was calculated to be worth +23 mk when replaced with D₂O.*

The calculated worth of the safety rod agrees well with the measured worth, but the decrease in reactivity produced by adding Lucite is overestimated by the calculation.

The cylindrical model used to describe a safety rod cell is an approximation. First of all, the cadmium, which is 0.0635 cm thick, was smeared over a region 1.48 cm thick. Secondly, in the cell calculations, the effect that the surrounding lattice has on the spectrum in the safety rod cell was neglected. For these reasons, the excellent agreement

between calculated and measured worth may be fortuitous. Calculation of the worth of the Lucite might be improved by a more rigorous method in which the geometry of the safety rod cell is represented more exactly.

Calculations of the worth of a safety rod, at various radii in the PRCF, have been reported earlier.⁽¹⁶⁾ The method of Nordheim and Scalettar was used in these calculations, and the calculated worths were normalized to the worth measured for a safety rod at a radius of 16 in. The calculated worth of a safety rod at 0.1 times the core radius is 44 mk. When this calculation is extrapolated to the center of the reactor, one obtains a worth of 46 mk, which is somewhat higher than the measured worth of 40.7 mk.

Errors

The error in a measurement of the absolute worth of the safety rod is due to uncertainties in the quantities $(1-k_{eff1})$ and A in Equation 1. The uncertainties in the counting rates N_1 and N_2 were negligible. The error in A was $\pm 3.1\%$, and the error in $(1-k_{eff1})$ was $\pm 1.1\%$. The error in a measured Δk_{eff} is $\pm 3.3\%$ or ± 1.3 mk. The error that is reported for the worth of the safety rod, ± 0.6 mk, is the standard deviation of the average of the results from three chambers.

The errors in supercritical reactivity measurements are due to uncertainties in period measurements and in the control rod calibration. The uncertainty in a reactivity value, as determined from a period measurement, is $\sim \pm 0.003$ mk. The errors in differential control rod worths (Table I) include an uncertainty of 0.005 mk for positioning of the control rod. This is a measure of how accurately control rods can be positioned in the PRCF.

An additional uncertainty is introduced when reactivities in dollars are converted to units of milli-k. This is because

of the uncertainty in the effective fraction of delayed neutrons β_{eff} , which is used to convert dollars to milli-k. But even if β_{eff} were in error by as much as 50%, the qualitative conclusions drawn from this experiment would not be affected.

REFERENCES

1. R. A. Bennett and L. C. Schmid. Approach to Critical and Calibration Experiments in the Plutonium Recycle Critical Facility, HW-80206. General Electric Company, Richland, Washington. July 1964.
2. M. D. Freshley. Plutonium Spike Fuel Elements for the PRTR Part I - The Mark I-G, HW-69200, Pt. 1, 1961.
R. E. Sharp. Plutonium Spike Fuel Elements for the PRTR Part II - The Mark I-H, HW-69200, Pt. 2, General Electric Company, Richland, Washington. 1961.
3. M. K. Millhollen. Specifications for Swaged UO₂ 19-Rod Cluster, PRTR Fuel Element Mark I, HW-64359. General Electric Company, Richland, Washington. 1960.
4. R. C. Liikala and W. P. Stinson. "Experimental and Analytical Results for PuO₂-UO₂-H₂O Lattices," Trans. Am. Nucl. Soc., vol. 9, no. 1, p. 127. June 1966.
5. U. P. Jenquin and V. O. Uotinen. Unpublished Data. Pacific Northwest Laboratory, Richland, Washington. 1966.
6. J. L. Carter, Jr. Unpublished Data. General Electric Company, Richland, Washington. 1964.
7. H. C. Honeck. THERMOS, A Thermalization Transport Theory Code for Reactor Lattice Calculations, BNL-5826. Brookhaven National Laboratories, Upton, New York. 1961.
8. R. H. Shudde and J. Dyer. NAA Program Description TEMPEST, A Neutron Thermalization Code, North American Aviation, Downey, California. 1960.
9. J. R. Lilley. Computer Code HFN Multigroup Multiregion Neutron Diffusion Theory in One Space Dimension, HW-71545. General Electric Company, Richland, Washington. November 17, 1961.
10. K. B. Stewart. "BNW Master Library," vols. I, II, III, BNWL-CC-325. Pacific Northwest Laboratory, Richland, Washington. September 1, 1965.
11. H. C. Honeck. "An Incoherent Thermal Scattering Model for Heavy Water," Trans. Am. Nucl. Soc., vol. 5, no. 1. 1962.
12. M. Nelkin. "Scattering of Slow Neutrons by Water," Phys. Rev., vol. 119, pp. 741-746. 1960.
13. U. P. Jenquin. Unpublished Data. Pacific Northwest Laboratory, Richland, Washington. 1966.

14. J. R. Worden, W. L. Purcell, and L. C. Schmid. Physics Experiment--High Power Density Core of the PRTR, BNWL-221. Pacific Northwest Laboratory, Richland, Washington. 1966.
15. V. O. Uotinen and L. C. Schmid. Unpublished Data, Atomic Products Operation, General Electric Company, Richland, Washington. 1963.
16. H. Sakata and L. C. Schmid. Safety Rod Interaction in the PRCF, BNWL-130. Pacific Northwest Laboratory, Richland, Washington. August 1965.

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