PLUTONIUM LATTICE EXPERIMENT
IN UNIFORM TEST LATTICE
OF UO_2 -1.5% PuO_2 FUEL

by

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PREFACE

This research was conducted under the auspices of the U.S. Atomic Energy Commission Plutonium Utilization Program (PUP). The Pacific Northwest Laboratories Division of Battelle Memorial Institute (PNL) conducts the PUP for the USAEC. The objective is to develop a firm technological base for the safe and economical use of plutonium as a fuel material in power reactors. To meet this objective, all available information that bears on the problems associated with plutonium utilization in commercial reactors is being integrated into the program. In addition, cooperative activities that are responsive to solving some of these problems have been initiated between industry and PNL. As a result, the basic technology of plutonium recycle will be efficiently translated into industrial recycle capability. This report contains the results of research conducted by Babcock & Wilcox and represents such a cooperative activity.

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1. INTRODUCTION

The plutonium lattice experiments are conducted to provide data for verification of the analytical methods and models developed for the design of water-moderated plutonium recycle cores. Because of the great expense of performing conventional critical experiments with a variety of fuels, the program is restricted to "small lattice experiments" (SLE), which are essentially PC^{TR}¹ measurements that require a relatively small region of the test fuel surrounded by buffer and driver regions of conventional fuel. The system is tailored to provide a critical assembly with a small central test region having a nearly flat flux and asymptotic spectrum. The test region is incrementally poisoned with boric acid until a void substitution yields a null reactivity change. This gives a precise measure of the boron concentration required to reduce to unity the infinite medium multiplication factor of the test lattice. Comparison of this number with the corresponding analytical prediction is a sensitive and direct check on the adequacy of the theoretical procedures. Various other measurements are also taken on the poisoned and unpoisoned test lattice for other tests of the analytical methods and to facilitate the deduction of k_{∞} for the unpoisoned lattice.

This report describes the facility, the equipment, and the techniques of measurement and presents the results of the measurements.

2. FACILITY AND CORE DESCRIPTION

2.1. Facility

The primary facility for the small lattice experiments (SLE) is a 5-1/2-foot-diameter core tank with associated rod drives, source drive, and water handling equipment (Figures 2-1 and 2-2). A small inner tank 7 inches in ID has been added to partition the central test lattice from the UO_2 driver. This tank has an independent water-handling system, as shown in Figure 2-3. The grid structure for the driver and the central lattice construction are shown in Figures 2-4 and 2-5, respectively.

The control and safety rod system uses variable-speed cable drum drives, which have proved to be extremely reliable. The drive motor is coupled by a magnetic clutch to the cable drum, which releases on a scram signal, allowing the rod to fall by gravity. An air piston and a hydraulic snubber stop the rod smoothly at its "zero" position.

The reactor normally operates with the following minimum instrumentation:

1. At least two neutron level circuits responding to ion chamber current and capable of initiating a scram.
2. At least one period trip circuit responding to a neutron-sensitive ion chamber current and capable of initiating a scram.
3. At least one linear picoammeter measuring current from a neutron-sensitive ion chamber.
4. At least one channel employing a proportional or fission pulse counter for startup.
5. A remote-area radiation monitoring system and a continuous air monitoring system.

Figure 2-6 is a block diagram of the nuclear instrumentation, and Figure 2-7 shows the instrumentation console.

2.2. Core

Three different types of fuel have been used in the current series of experiments. These are 4% UO_2 used in the driver region for all measurements, 2.5% UO_2 used for the test lattice in the initial small lattice experiments, and UO_2 -1.5% PuO_2 used in the test lattice for the most recent measurements. The two types of UO_2 fuel were used previously in other physics verification measurements. The PuO_2 fuel was recently obtained from the AEC; it was previously used in subcritical experiments by General Electric. Table 2-1 lists the properties of each of the fuel types. Figure 2-8 is a photograph of three of the plutonium rods.

The general lattice configuration used for the plutonium SLE measurements is shown in Figure 2-9, and the dimensions and compositions are given in Table 2-2.

The test region is the central third of region 1 in the vertical direction. Over this region an essentially flat flux and asymptotic spectrum are produced by poisoning k_∞ to unity and suitably adjusting the buffer. The condition $k_\infty = 1$ is determined by balancing the reactivity worth of the test region lattice with that of a void can substituted for the test lattice. The top and bottom thirds of region 1 serve as vertical buffers and have the same composition as the test region. Region 2 constitutes the radial buffer and has the same composition as the test region, although it could be adjusted if necessary for flux flattening or spectrum tailoring.

Region 3 is a thin transition region which includes four grid support rods and the water gap between the buffer lattice and the inner tank wall. Region 4 is the 1/4-inch-thick inner tank wall. Region 5 is an outer transition, including the water gap between the inner tank and the driver. Region 6 is the driver, consisting of a 4% UO_2 lattice. Since the test and buffer regions are poisoned, the driver region is enlarged to maintain criticality. Region 7 is a water reflector of effectively infinite extent.

The method of loading the central lattice after the critical conditions have been established is shown in Figure 2-10. The central lattice is divided into three vertical regions, as shown in Figure 2-5. Figure 2-11 shows the void can and the movable test region of the central lattice

in more detail. The void can is a thin-walled aluminum extrusion with welded end caps; it is 27 inches long, overall, and weighs 1870 grams.

Table 2-1. Fuel Properties

	<u>4% UO₂</u>	<u>2.5% UO₂</u>	<u>PuO₂-UO₂</u>
Cladding OD, in.	0.4755	0.4748	0.562
Cladding thickness, in.	0.016	0.032	0.030
Cladding material	304 SS	6061-T6 Al	Zircaloy-2
Fuel pellet diameter, in.	0.444	0.4054	0.491
Active fuel length, in.	66.7	60.37	24
Total length, in.	71.5	61.59	25
Fuel density, g/cm ³	9.46	10.29	10.21
Weight of fuel per rod, g	1600	1306	760
Weight % UO ₂	100	100	98.5
Weight % PuO ₂	--	--	1.5 ^(a)
Weight % ²³⁵ U in U	4.020	2.46	Natural

(a) ²³⁸Pu — 0.02%,

²³⁹Pu — 81.26%,

²⁴⁰Pu — 16.33%,

²⁴¹Pu — 2.13%,

²⁴²Pu — 0.26%.

Table 2-2. Dimensions and Compositions of the Small Lattice Experiments

Region No.	Designation	Composition	Effective radius, cm
1	Test region	a. 2.5% UO_2 rods in H_2O , 0.640-in. pitch	2.715
		b. 1.5% $\text{PuO}_2\text{-UO}_2$ rods in H_2O , 0.747-in. pitch	3.211
2	Buffer	a. 2.5% UO_2 rods in H_2O , 0.640-in. pitch	8.652
		b. 1.5% $\text{PuO}_2\text{-UO}_2$ rods in H_2O , 0.747-in. pitch	8.361
3	Inner transition region	a. Al in H_2O , M/W = 0.4365	8.890
		b. Al in H_2O , M/W = 0.0462	8.890
4	Inner tank	Al	9.525
5	Outer transition region	H_2O	9.980
6	Driver	a. 4% UO_2 rods in H_2O , 0.595-in. pitch	19.161
		b. 4% UO_2 rods in H_2O , 0.595-in. pitch	20.051
7	Reflector	H_2O	83.820

Figure 2-1. General View of the SLE Facility

Figure 2-2. Plan View of Bay 1

Figure 2-3. Schematic Diagram of Water Loop

Figure 2-4. Grid Structure for the Driver

Figure 2-5. Central Lattice

Figure 2-6. Block Diagram of Instrumentation

Figure 2-7. SLE Instrumentation and Control Console

Figure 2-8. PuO_2 Fuel Rods

Figure 2-10. SLE Core With Central Lattice Partially Withdrawn

Figure 2-11. Test Region and Void Can

3. MEASUREMENTS AND RESULTS

3.1. System Operating Characteristics

In order to evaluate the tentative SLE techniques, the SLE facility was initially loaded with 2.5% UO_2 rods in the central region. Following the experimental determination of the critical loading for this system, preliminary experiments were performed to determine the operational characteristics of the system. These included control rod calibration, power calibration, and isothermal temperature coefficient measurements. For the initial loading with the dimensions given in Table 2-2, the excess reactivity was 55¢ and the peripheral fuel rods were worth about 5¢ each. The total rod worth was about 5% $\Delta k/k$, the power calibration for linear channel 1 was 2.7 watts/nanoampere, and the temperature coefficient was $-2 \times 10^{-5} \Delta k/k - ^\circ\text{F}$ over the range from 79 to 109 F. Various other measurements were performed on this test lattice (poisoned and unpoisoned). These included the thermal disadvantage factor, fission cadmium ratio, thermal and epithermal flux profiles, and power distribution. The results of the UO_2 SLE measurements are given in reference 2.

After this series of UO_2 SLE measurements the assembly was loaded with 1.5% PuO_2 - UO_2 fuel in the central region. As described in Table 2-2, the excess reactivity was 150¢, and the peripheral fuel rods were worth about 5¢ each. The total rod worth was about 6% $\Delta k/k$; the power calibration for linear channel 1 was 2.9 watts/nanoampere, and the temperature coefficient was $-1 \times 10^{-5} \Delta k/k - ^\circ\text{F}$ over the range from about 86 to 108 F.

3.2. Thermal Disadvantage Factor Measurements

The thermal disadvantage factor was measured in the clean core and in the borated core (2440 ppm). The thermal disadvantage factor is defined as the ratio of the average thermal neutron flux in the moderator to the average thermal neutron flux in the fuel of a unit cell. The measurements were taken by activating 7-mil-thick dysprosium (5 wt %) and

aluminum alloy sector foils in the moderator and 0.482-inch-diameter foils in the split pin. Two data foils—one sector and one round—and two monitor foils were used in each bare activation.

The bare foil for measuring the flux in the fuel was placed in a split pin in the center of the test region. A sector foil was used to measure the flux in the moderator; it was shaped to fit in the water gap between the fuel rods in the test region. This was held in place with thread laced under and over the foil and around the four adjacent rods. The foil was positioned at the same core height as the round foil in the split pin.

The cadmium-covered measurements were also obtained with 7-mil dysprosium-aluminum foils. Since it was not practical to cover the sector foil with cadmium, a round foil was used to measure the epicalcium flux in the moderator. Because of space limitations in the moderator channel, the foil was positioned vertically in the center of the moderator channel in a cadmium box. This was not serious, since the cadmium ratio was only a small correction to the desired thermal disadvantage factor. The cadmium-covered foil in the split fuel pin was covered on each side by a 0.020-inch-thick cadmium disc and placed in a cadmium sleeve 0.055-inch long. The bare and cadmium-covered runs were normalized by using two 0.259-inch-diameter Dy-Al foils located on the monitor rod. The geometry of loading and cadmium covering is shown in Figure 3-1.

The foils were activated at a constant power level for 20 minutes. The exposure clock was started when the reactor power reached $1/e$ times the final power. Since the half-life of dysprosium-165 is only 139 minutes, the same foils were used repeatedly.

The Dy-Al foils were counted in the 4π gas-flow proportional counter. The procedure is as follows: (1) place the foil in the counter, (2) flush vigorously with methane for 3 minutes, (3) turn on the high voltage, (4) flush for an additional 3 minutes, and then (5) take four 1-minute counts. At least 45 minutes was always allowed for decay of short-lived aluminum and dysprosium isotopes before counting was started.

After counting, the data were reduced to saturated activity and factors were applied to correct each datum point for the following:

1. Foil dysprosium content and counter efficiency (foil factor).
2. Axial flux gradient (position factor).
3. Epicadmium activity.

Foil factors were determined by irradiating a set of bare foils on a rotating wheel to permit correcting the foil data for differences in dysprosium content, in counter efficiency, and in foil weight and size.

Measurements of the disadvantage factor (not corrected for streaming) in the clean test region yielded a moderator-to-fuel flux ratio of 1.196 ± 0.037 , and measurements in the borated core (2440 ppm) yielded a flux ratio of 1.102 ± 0.044 .

3.3. Flux and Null-Reactivity Measurements

The major part of the experimental program was devoted to the measurement of thermal flux and null reactivity between the test lattice and the void can. In theory, k_{∞} can be derived from the quantity of poison distributed through the test region and producing the same reactivity obtained from a void occupying the same volume. The accuracy of the measurement depends on the flatness or constancy of the flux across the test region. The flatness of the flux was determined by activating bare and cadmium-covered gold foils 0.259-inch in diameter and 0.005-inch thick. The bare foils were placed in holes punched in steel strips and held in place with Teflon tape 0.0035-inch thick. The cadmium-covered foils were placed in 0.020-inch-thick cadmium boxes and fastened to the same strips with Teflon tape. The foils were spaced at 0.747-inch intervals in the test and inner buffer regions and at 0.595-inch intervals in the outer buffer and driver regions for the radial measurements and at 1.969-inch (5 cm) intervals for the axial measurements.

The radial distribution was measured at the horizontal midplane of the core, and the axial distribution was measured in the moderator channel next to the central fuel rod.

The foils were activated at a constant power for 20 minutes. The activated foils were counted (once on each side) in each of three gas-flow end window proportional counters, and then the saturated activities were computed. Runs were normalized by means of gold foils on the monitor rod. The results of the bare and cadmium-covered radial and

axial gold activations in the clean core are given in Figures 3-2 and 3-3, and the results at 2440 ppm are given in Figures 3-4 and 3-5.

Figure 3-4 shows that the radial flux is essentially flat and asymptotic through the test region. Figure 3-5 indicates that, although the thermal-to-epithermal axial flux ratio is essentially constant along the axis at the horizontal midplane of the test region, the thermal and epithermal flux both have variation in the test region. However, there should be no detectable effect on the null reactivity measurement.

The measured worth of the void can relative to the nine-rod test lattice was found to be -110.2¢ for the clean lattice. With the test and inner buffer regions poisoned with boric acid solutions of various concentrations, the reactivity differences were remeasured. These data were subjected to a least-squares fit and yielded a boron concentration of 2439 ± 30 ppm for the null reactivity condition.

In addition to the void can substitution, a solid aluminum can was substituted for the nine-rod test lattice. The measured worth of the solid can relative to the void can was found to be -13.0¢ for the clean lattice.

Since the weight of aluminum in the void can is 1870 grams, and the test lattice has aluminum end grids weighing about 764 grams, the net excess aluminum in the void can is 1106 grams. Using the measured worth of the aluminum and the boric acid in the test region, a correction was applied to the boron concentration for the null-reactivity condition. The corrected boron concentration for the null-reactivity condition was 2243 ± 30 ppm.

3.4. Derivation of k_{∞}

In reference 3, the infinite medium multiplication factor of an unpoisoned ^{235}U -fueled medium was expressed as

$$k_{\infty} = \left(\frac{\eta^{\text{th}}}{\eta_p} \right) \left(\frac{f}{f_p} \right) \left(\frac{\epsilon}{\epsilon_p} \right) \left(\frac{p}{p_p} \right) \frac{(1 + \delta_{25}^{\infty})}{(1 + \delta_{25}^{\infty})_p}, \quad (3-1)$$

where the subscript p refers to the poisoned medium that gives a null-reactivity condition. Other quantities are defined as follows:

$$\eta_{25}^{th} = \frac{\text{fission neutrons from thermal absorptions in } ^{235}\text{U}}{\text{thermal neutrons absorbed in } ^{235}\text{U}},$$

$$f = \frac{\text{thermal neutrons absorbed in } ^{235}\text{U}}{\text{total thermal neutrons absorbed}},$$

$$\epsilon = \frac{\text{total fission neutrons from } ^{235}\text{U and } ^{238}\text{U}}{\text{total fission neutrons from } ^{235}\text{U}},$$

$$p = \frac{\text{total thermal neutrons absorbed}}{\text{total neutrons absorbed}},$$

$$1 + \delta_{25}^{\infty} = \frac{\text{total fission neutrons from } ^{235}\text{U}}{\text{fission neutrons from thermal absorptions in } ^{235}\text{U}}.$$

A similar expression holds in the present case if fissile is substituted for ^{235}U and fertile for ^{238}U . In reference 3, k_{∞} was obtained by two methods: In one case, all available experimental data were used in the ratios. In a second case, only (f/f_p) was obtained from experimental data and the other ratios were calculated. The values of k_{∞} derived by the two methods for the three lattices studied differed by no more than 0.3%, and in all cases the uncertainty associated with the second method was smaller than that with the first method. This suggests that some cancellation of errors occurs when all ratios other than (f/f_p) are calculated.

Additional ratios will be measured on this lattice and k_{∞} will be derived using the equivalent of equation 3-1. In the meantime, the k_{∞} value derived below gives a tentative value by a method similar to the second method of reference 3. It differs only in that the disadvantage factor in the calculation is not forced to the experimental value.

The following procedure was used to derive k_{∞} for the unpoisoned lattice from the experimental data. k_{∞} was calculated for a poison concentration of 2243 ppm boron with the buckling set equal to zero, i.e.,

$$k_{\infty}^p (\text{calculated}) = 1.0009.$$

For this case

$$k_{\infty} (\text{measured}) = 1.0000.$$

Using the same computer code, k_{∞} was calculated for the clean lattice with zero boron concentration and zero buckling.

$$k_{\infty}^c (\text{calculated}) = 1.2713.$$

Then, normalizing the calculation to match the measured critical condition, the best value of k_{∞} for the clean lattice is

$$k_{\infty} = k_{\infty}^c (\text{calculated}) \times \frac{k_{\infty} (\text{measured})}{k_{\infty}^p (\text{calculated})} = 1.2702.$$

In addition to this, k_{∞} was calculated for the fundamental mode, i. e., zero boron concentration and finite buckling:

$$k_{\infty}' (\text{calculated}) = 1.2684.$$

Then, normalizing the calculation to the measured critical condition, the best value for k_{∞}' for the clean lattice is

$$k_{\infty}' = \frac{k_{\infty}' (\text{calculated}) \times k_{\infty} (\text{measured})}{k_{\infty}^p (\text{calculated})} = 1.2673.$$

Figure 3-1. Loading Arrangement for Thermal Disadvantage Factor Measurement

Figure 3-2. Radial Flux Distribution — Unpoisoned Test and Buffer

Figure 3-3. Axial Flux Distribution — Unpoisoned Test and Buffer

Figure 3-4. Radial Flux Distribution — Poisoned Test and Buffer

Figure 3-5. Axial Flux Distribution — Poisoned Test and Buffer

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Paulson, AE
Pettus, WG
Poor, HH/Alliance
Probert, PB/Barberton
Roy, DH
Schuler, TM
Snidow, NL
Stern, ME
Travis, CC/TRG
Turner, RA
Webb, RA
Whitaker, BW
Wittkopf, WA