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SPECTRAL SHIFT CONTROL REACTOR
BASIC PHYSICS PROGRAM
QUARTERLY TECHNICAL REPORT
NUMBER 10

January-March 1963

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THE BABCOCK & WILCOX COMPANY
NUCLEAR DEVELOPMENT CENTER

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THE UNITED STATES ATOMIC ENERGY COMMISSION
By
THE BABCOCK & WILCOX COMPANY
Nuclear Development Center
Lynchburg, Virginia

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ABSTRACT

This report summarizes the work performed on the Spectral Shift Control Reactor Basic Physics Program during the tenth contract quarter. The major objective of this program is to study the nuclear properties of slightly enriched uranium oxide lattices moderated by D_2O - H_2O mixtures.

Critical experiments were performed on a perturbed uniform lattice of 2.46%-enriched UO_2 fuel rods having a nonmoderator-to-moderator volume ratio of 1.0 and moderated by a 72% D_2O - H_2O mixture. The following perturbations were studied: boron blade in uniform lattice, moderator gap in uniform lattice, boron blade in moderator gap, cadmium blade in moderator gap, aluminum blade in moderator gap, boron cruciform in moderator gap, and aluminum cruciform in moderator gap. In each case the reactivity worth of the perturbation and the local flux distribution were measured.

The conceptual design of a series of Small Lattice Experiments (SLE) was completed. The objective of this work is to measure k_{∞} , thermal disadvantage factor, and cadmium ratios of U^{235} and Th^{232} in a lattice of 93%-enriched UO_2 - ThO_2 ($N_{Th}/N_{235} = 15$) fuel rods. The nonmoderator-to-moderator volume ratio is 1.0, and the moderator composition is 70-80% D_2O .

Improvements in methods of analysis continued. A program (RIP) for computing near thermal-resonance and high-energy absorption for use in multigroup codes, particularly BPG, is described.

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1. INTRODUCTION

Summarized here is the work performed on the Spectral Shift Control Reactor (SSCR) Basic Physics Program during the period January 1 through March 31, 1963. Contract activities in preceding quarters are given in the referenced Quarterly Technical Reports.¹⁻⁹ The primary objective of this program is to study the nuclear properties of slightly enriched oxide fuels moderated by light and heavy water mixtures ranging in composition from zero to approximately 90% D₂O.

In the first phase of the program, completed early in 1962, uniform lattices of 4%-enriched UO₂ fuel rods were studied at a nonmoderator-to-moderator volume ratio (M/W) of 1.0. The results of critical experiments¹⁰, exponential experiments at room¹¹ and elevated¹² temperatures, and neutron age measurements¹³ (in a lattice of ThO₂ rods) are summarized in the referenced topical reports. The theoretical methods used to analyze and correlate the data are given in References 14 and 15.

In the second phase of the program, completed in December 1962, the variable of M/W ratio was extended to cover the range 1.2 to 0.7, and the variable of enrichment was extended to 2.46%-enriched UO₂. Critical experiment measurements of uniform lattice properties are given in References 7, 8, and 9. This phase also included Small Lattice Experiments (SLE) designed to investigate the applicability of the PCTR technique to epithermal lattices of the SSCR type. The results of this study are reported in Reference 9.

In the third phase of the program, which began in January 1963, emphasis was shifted to nonuniform lattice properties typical of those encountered in the design of power reactors. In a series of critical experiments (Task 23), the perturbations of a uniform lattice by control blades and moderator gaps are studied. The program includes

Small Lattice Experiments (Task 24) on lattices of 93%-enriched UO_2 - ThO_2 fuel rods moderated by 70 to 80% D_2O - H_2O mixtures. The analysis of experimental data continues (Task 25).

2. CRITICAL EXPERIMENTS (TASK 23)

(R. H. Clark, Task Leader; E. J. DeRoche,
G. T. Fairburn, J. W. Hallam)

2.1. Introduction

The objective of this task is to measure the effects of selective perturbations on the properties of a uniform lattice of 2.46%-enriched UO_2 fuel rods at a nonmoderator-to-moderator volume ratio (M/W) of 1.0. In one sequence of experiments the effects on reactivity and flux shape of the following perturbations are measured as a function of moderator composition.

Core XVIII - 72% D_2O

- A - Unperturbed uniform lattice
- B - Boral blade in uniform lattice
- C - Moderator gap in uniform lattice
- D - Aluminum blade in C
- E - Cadmium blade in C
- F - Boral blade in C
- G - Boral cruciform surrounded by gap
- H - Aluminum cruciform surrounded by gap

Core XIX - 50% D_2O + Boron

- A - Unperturbed uniform lattice
- B - Boral blade in uniform lattice
- C - Moderator gap in uniform lattice
- F - Boral blade in C

Core XX - 0% D₂O + Boron

- A - Unperturbed uniform lattice
- B - Boron blade in uniform lattice
- C - Moderator gap in uniform lattice
- F - Boron blade in C

Cores XIX and XX are poisoned with boric acid to keep the core diameter constant in all experiments.

In another sequence of experiments the effects on reactivity and flux shape of a partially inserted cruciform blade are measured. The experiments are performed in Core XVIII, and measurements are made with the cruciform fully in, one-third out, two-thirds out, and fully out. A small amount of boric acid is added to keep the critical height (and diameter) constant during this sequence of measurements.

The Core XVIII perturbations, excluding the cruciform cases, were studied during this quarter and are reported here.

2.2. Description of Core XVIII

Core XVIII was assembled in the 5-foot diameter aluminum core tank used throughout the program.¹⁰ The fuel rods were aligned and supported at each end by 1-inch thick aluminum egg-crate grid plates. Additional alignment for the fuel rods and perturbors near the plane of the flux traverses was provided by two 1/16-inch thick drilled aluminum sheets, as shown in Figure 2-1.

The fuel rods were 5-foot-long by 0.475-inch-OD by 0.032-inch-wall aluminum tubes filled with sintered pellets of 2.46%-enriched UO₂. The active (fuel) length was 60.37 inches, the pellet diameter was 0.405 inch, and the average pellet density was 10.3 gm/cm³. The properties of the fuel rods are given in more detail in Reference 8. Since the fuel rods were spaced on a square lattice pitch of 0.595 inch, the M/W ratio was 1.001. Figure 2-2 is a horizontal section through the unperturbed lattice showing the position of the peripheral fuel rods, the location of the safety blades when inserted, and the direction and extent of the flux traverses to be reported in Section 2.6. Note that the lattice is shifted one-half pitch from its position in all previous studies so that the geometrical center of the core now corresponds to a fuel rod.

Figure 2-3 is a view of the top of the core with one of the perturbors (cruciform) in place.

Six 8-inch-wide boral and cadmium blades were used as safety rods. The boral blades were approximately 0.080-inch thick, and the cadmium blades consisted of sheets of 0.020-inch-thick cadmium cemented between 0.020-inch-thick stainless steel sheets. As shown in Figure 2-2, Blades 1 and 4 were ganged. The reactivity worth of the blades, estimated from rod-drop measurements, was affected substantially by the type of perturbation in the core, as shown in Table 2-1. All reactivity and flux measurements were made with the safety blades fully withdrawn, and criticality was obtained by adjusting the moderator level.

Table 2-1. Reactivity Worth of Safety Blades

<u>Blade number</u>	<u>Blade material</u>	<u>Reactivity worth, dollars</u>
1	Cadmium/Cadmium	1.20 - 1.50
2	Boral	0.85 - 1.25
3	Cadmium	0.60 - 0.85
4	Boral/Cadmium	<u>1.80 - 2.30</u>
Total		4.45 - 5.90

The unperturbed core XVIII achieved criticality with 5137 fuel rods (Loading A) at a moderator composition of 72.1 mole % D₂O. The relation

$$\pi R^2 = (\text{number of rods}) (\text{pitch})^2$$

provided the equivalent core radius, 61.11 cm. The radial reflector thickness, given by the difference between the inner radius of the core tank and the core radius, was 15.1 cm. The critical moderator height, with all control blades withdrawn, was 107.8 cm. The critical parameters are summarized in Table 2-2.

Table 2-2. Critical Parameters of Core XVIII - A

<u>Parameter</u>	<u>Value</u>
Number of fuel rods	5137
Type of fuel	2.46%-enriched UO_2
Equivalent core radius, cm	61.11
Radial reflector thickness, cm	15.1
Critical moderator height, cm	107.8 ± 0.1
D_2O concentration, mole %	72.1 ± 0.1
Lattice pitch, cm	1.511 ± 0.003
Rod diameter, cm	1.206 ± 0.001
M/W ratio	1.001
Temperature, C	20 ± 1

2.3. Description of Perturbers

The dimensions and locations of the perturbers of the uniform lattice are given in Table 2-3 and Figure 2-4. The unperturbed uniform lattice is designated A. In perturbation B, a 10-inch boral blade was inserted in the uniform lattice between two rows of fuel rods, one-half lattice pitch from the center of the core. Seventeen fuel rods along the diameter of the core were removed to create the moderator gap, C, and in D, E, and F, 10-inch-wide aluminum, cadmium or boral blades were inserted in the center of this gap. G and H were formed by removing 21 fuel rods from the center of the core and inserting 6-inch-wide boral or aluminum cruciforms in the center of the gap. All perturbers extended from one inch above the bottom of the core to several inches above the top of the fuel rods.

Table 2-3. Dimensions of Perturbers

<u>Loading</u>	<u>Geometry</u>	<u>Composition</u>	<u>Width, in.</u>	<u>Thickness, in.</u>
A	(unperturbed lattice)		--	--
B	Blade	Boral	10.0 ± 0.1	0.097 ± 0.002
C	(moderator gap)		1 rod	17 rods
D	Blade	Aluminum	10.0 ± 0.1	0.090 ± 0.002
E	Blade	Cadmium	10.0 ± 0.1	0.090 ± 0.002
F	Blade	Boral	10.0 ± 0.1	0.093 ± 0.002
G	Cruciform	Boral	6.00 ± 0.04	0.093 ± 0.003
H	Cruciform	Aluminum	6.02 ± 0.03	0.090 ± 0.001

The aluminum blade and aluminum cruciform (D and H) were fabricated of #6061 aluminum. The cadmium blade E consisted of a sheet of 0.020-inch-thick cadmium cemented between two 0.032-inch-thick sheets of stainless steel (#304) with 0.003-inch-thick Mylar adhesive tape. Boral is a mixture of natural B_4C and aluminum, clad on both sides with aluminum. The meat is approximately 35 wt % B_4C and has a density of about 2.63 gm/cm^3 ; the aluminum is commercially pure. Table 2-4 lists preliminary values for the composition of the boral. More accurate analyses will be reported later.

Table 2-4. Preliminary Values for Composition of
Boral Blades

<u>Loading</u>	<u>Thickness, mils</u>			<u>Meat composition, gm B_4C/cm²</u>
	<u>Total</u>	<u>Meat</u>	<u>Clad</u>	
B	97	65	16	0.153
F	93	63	15	.147
G	93	63	15	0.147

2.4. Reactivity Measurements

Preliminary values for the reactivity worths of the perturbations in Core XVIII were obtained from their critical moderator heights and the integrals of $\partial\rho/\partial h$ measurements. The critical moderator heights were measured by a calibrated manometer, accurate to at least ± 0.1 cm. The accuracy of $\partial\rho/\partial h$ measurements was approximately $\pm 3\%$, based on the uncertainties in the inhour relation and a relative error of ± 0.05 cm in Δh measurements by a conductivity-probe. To avoid difficulties from delayed photoneutrons, only one period measurement was made for each run. Figure 2-5 gives $\partial\rho/\partial h$ as a function of the average moderator height, i.e., the average of the critical height and the height when the period was measured, as well as the integral of $\partial\rho/\partial h$ vs h relative to 145 cm. Figure 2-6 is a plot of the same data correlated against $(\partial\rho/\partial h)^{-1/3}$.

The results are summarized in Table 2-5, where all data were taken at 20 ± 1 C. Although the radial dimensions of each loading were the same, i.e., the core diameter was constant, the number of fuel rods was changed in some loadings to create moderator gaps near the perturbors. The excess reactivity is given two ways, relative to a moderator height of 145 cm (full height) and relative to 107.8 cm (the critical height of the unperturbed lattice). The reactivity values are accurate to at least $\pm 5\%$ and can be converted to absolute units using a provisional value for β_{eff} of 0.0069 in this core.

Comparative reactivity measurements by another technique are now in progress and will be reported next quarter. In these experiments boric acid is added to the moderator to calibrate moderator height against boron concentrations. Thus the reactivity worth of the perturbors will be obtained in terms of boron concentration for constant critical moderator height (and diameter).

Table 2-5. Reactivity of Perturbations in Core XVIII

Loading designation and description	Number of fuel rods	Critical moderator height, cm	Reactivity, cents	
			Relative to h = 145 cm	Relative to h = 107.8 cm
A - Unperturbed lattice	5137	107.8	234	0.0
B - Boral blade in lattice	5137	143.0	7.5	-227
C - Moderator gap	5120	101.9	294	60
D - Aluminum blade in C	5120	103.2	281	47
E - Cadmium blade in C	5120	128.1	80	-154
F - Boral blade in C	5120	144.2	2.9	-231
G - Boral cruciform	5116	145.0	0.0	-234
H - Aluminum cruciform	5116	102.0	293	59

2.5. Buckling and Reflector Savings

2.5.1. Critical Buckling

The critical buckling of the unperturbed lattice of Core XVIII-A was derived from two radial and three axial flux traverses with bare and cadmium-covered 0.259-inch-diameter by 0.005-inch-thick gold foils. The foils, mounted on 0.005-inch-thick by 0.5-inch-wide steel tapes, were spaced 5 cm axially and 1.511 cm radially (3.022 cm for cadmium-covered runs). The radial traverses were made in a plane 65 cm above the bottom of the fuel, and the axial traverses were made 4.5 pitches south and 9.5 pitches east of the core center.

The foils were activated for 20 minutes at power levels between 200 and 400 watts with all control blades withdrawn and were beta counted for 1 minute on each side in each of three end-window, gas-flow proportional counters. Count rates were at least 40,000 counts/min. Bare and cadmium-covered runs were normalized by four gold monitor foils.

Radial and axial bucklings were computed by least squares fitting the saturated activities in the asymptotic regions to the functions

$$J_0 \left[B_r (r - r_0) \right] \text{ and } \cos \left[B_z (z - z_0) \right].$$

Based on a constant gold-cadmium ratio of about 1.45, the asymptotic region extended to a radius of at least 48 cm (extent of data) and between about 15 and 95 cm in the axial direction. Within these ranges B_r and B_z were constant.

The results of the measurements are listed in Table 2-6. A small correction

$$\Delta B_z = -\frac{B_z^2}{\pi} \Delta h$$

was applied to reduce the data to the unperturbed critical moderator height of 107.8 cm.

Table 2-6. Critical Buckling of Core XVIII-A

Run number	Type of traverse	Buckling, $\times 10^{-4} \text{ cm}^{-2}$		
		Radial	Axial	Total
706	Bare	8.78 ± 0.07	6.00 ± 0.03	--
707	Cd covered	8.74 ± 0.06	6.00 ± 0.05	--
729	Cd covered	--	6.00 ± 0.05	--
Best value		8.76 ± 0.06	6.00 ± 0.05	14.76 ± 0.08

Since the critical moderator height was 107.8 cm and the critical radius was 61.11 cm, the radial and axial reflector savings are

$$\lambda_r = 20.1 \pm 0.3$$

$$\lambda_z = 20.6 \pm 0.6.$$

2.5.2. Axial Reflector Savings

Axial bucklings were measured in some of the perturbed loadings of Core XVIII to obtain the variation of axial reflector savings with critical moderator height. The axial flux traverses were made with bare gold foils, spaced on 5-cm intervals and usually located 4.5 pitches south and 9.5 pitches east of the core center. To check for possible variation in axial buckling with radial position, two such measurements were made in Core XVIII-G (cruciform), one along the core axis and one 15 pitches from the core axis.

The results are summarized in Table 2-7 and Figure 2-7. A small correction has been made for the difference between the critical moderator height, unperturbed by foils and foil holders, and that during the flux traverse. As predicted by the $\partial\rho/\partial h$ (Figure 2-6), the axial reflector savings remains constant for moderator heights below 130 cm. The axial reflector savings for the loading containing the boron cruciform (Loading G) appears to be 1 cm less when measured along the core axis, i.e., axis of the perturber. Although this reduction can be attributed to the perturber in the top reflector (and absence of some fuel rods), which may locally reduce the reflector effectiveness, the discrepancy is within the combined errors of the two measurements.

Table 2-7. Axial Buckling and Reflector Savings
Vs Critical Height

Loading number	Moderator height, cm	Axial buckling $B_z, 10^{-2} \text{ cm}^{-1}$	Axial reflector savings $\lambda_z, \text{ cm}$
A	107.8 ± 0.1	2.426 ± 0.010	20.6 ± 0.6
B	143.0 ± 0.1	1.967 ± 0.006	16.7 ± 0.5
C	101.9 ± 0.1	2.570 ± 0.012	20.3 ± 0.6
E	128.1 ± 0.1	2.114 ± 0.010	20.5 ± 0.7
F	144.2 ± 0.1	1.943 ± 0.004	17.5 ± 0.4
G	145.0 ± 0.1	1.946 ± 0.007	16.6 ± 0.6
G ^(a)	145.0 ± 0.1	1.956 ± 0.007	15.5 ± 0.6

(a) Along core axis.

2.6. Flux Distribution

2.6.1. Procedure

Flux distributions in the vicinity of the perturbers of Core XVIII were mapped with bare and cadmium-covered gold and Dy-Al foils. The gold foils were 0.259 inch in diameter by 0.005 inch thick; the Dy-Al foils were 0.259 inch in diameter by 0.007 inch thick and contained approximately 5 wt % dysprosium. The Dy-Al foils were irradiated in a constant flux, and their activities were counted to calibrate for dysprosium content; matched sets of gold foils were selected by weights. For cadmium-covered runs the foils were placed in small cadmium pill boxes having 0.020-inch-thick walls.

The flux traverses were made across the perturbers in a plane 65 cm above the bottom of the fuel. The foils were mounted on 0.005-inch-thick by 0.5-inch wide spring-steel foil holders, which were accurately aligned relative to the perturber and adjacent fuel rods. Near the perturber, the foils were spaced every lattice pitch for bare runs and at double pitch intervals for cadmium-covered runs, and the spacing was increased at greater distances.

The foils were activated for 20 minutes at power levels in the range of 50 to 400 watts, with all control blades withdrawn, and then beta counted for 1 minute in each of three end-window, gas-flow proportional counters. Count rates were at least 10,000 counts/min except for some of the cadmium-covered Dy-Al foils where count rates were occasionally as low as 1000 counts/min. Bare and cadmium-covered runs were normalized by four gold monitor foils located near the edge of the core.

In two of the perturbation studies, fine structure measurements were made at quarter-pitch intervals with 0.020-inch diameter by 0.5-inch long Dy-Al (5 wt % Dy) wires. For the cadmium-covered runs, the wires were placed in 0.075-inch-OD by 0.020-inch-wall cadmium tubes, pinched off at the ends. The same calibration, irradiation, and counting procedures were used.

2.6.2. Results

The results of the flux measurements through the perturbors, except the boron cruciform to be reported next quarter, are shown in Figures 2-8 through 2-22. Although traverses were made on both sides of the perturbors to show that the perturbors were accurately positioned, the data reported are averages of the north and south traverses, since symmetry was observed within 1 to 2%. The slight asymmetry is attributed to the displacement of the geometrical center of the core one-half lattice pitch south and west from the geometrical center of the core tank.

Corresponding bare and cadmium-covered runs for each perturber are normalized. For the gold traverse, the thermal flux is proportional to the difference between normalized bare and cadmium-covered activities. For the Dy-Al traverses, since the cadmium ratio was so large, the thermal activity was obtained by multiplying the bare activity by $(C-1)/C$, where C is the Dy-Al foil cadmium ratio. To permit approximate comparisons of thermal fluxes between perturbations, the thermal activities are also internormalized (on the basis of unity for the bare gold activity at the center of the unperturbed lattice). It is emphasized that this internormalization is only approximate because the perturbors changed the flux level slightly, even at the remote location of the monitor foils.

Two independent measurements of the thermal flux shape were made in each case, i. e., that derived from gold and that from Dy-Al traverses. Statistically, the thermal flux derived from Dy-Al traverses is superior because the cadmium ratio is very high and the cadmium-covered activity provides a small correction to the bare activity. For gold, since its cadmium ratio is so low, 1% errors in bare and cadmium-covered activities produce a 5% error in the thermal activity.

As shown in the figures, however, the ratio of thermal activity derived from Dy-Al to that derived from gold departs from a constant value near the perturber. This deviation is attributed to spectral effects. The activation cross section of dysprosium decreases faster than $1/v$ below the cadmium cutoff, and the activation cross section of gold decreases slower than $1/v$ near 0.4 ev. The thermal gold data are also very strongly affected by systematic errors in the cadmium-covered traverses, such as epicadmium absorptions in the 0.020-inch-thick cadmium covers¹⁶ and changes in the effective cadmium cutoff energy near the perturber. These problems will be considered further in the next quarter.

Figure 2-1. Core XVIII - Vertical Section

Figure 2-2. Core XVIII - Horizontal Section

Figure 2-3. View of Core XVIII-G

Figure 2-4. Location of Perturbers

B - Boral Blade in Uniform Lattice

C - Moderator Gap in Center of Lattice

D - Aluminum Blade in Gap

E - Cadmium Blade in Gap

F - Boral Blade in Gap

G - Boral Cruciform in Gap

H - Aluminum Cruciform in Gap

Figure 2-5. $\partial\rho/\partial h$ Vs h for Core XVIII

Figure 2-6. $(\partial\rho/\partial h)^{-1/3}$ Vs h for Core XVIII

Figure 2-7. Axial Buckling and Reflector Savings

Figure 2-8. Flux Distribution With Boral Blade in Lattice
(B) - Gold

Figure 2-9. Flux Distribution With Boral Blade in Lattice
(B) - Dy

Figure 2-10. Flux Distribution With Boral Blade in Lattice
(B) - Thermal

Figure 2-11. Flux Distribution With Moderator Gap in Lattice
(C) - Gold

Figure 2-12. Flux Distribution With Moderator Gap in Lattice
(C) - Dy

Figure 2-13. Flux Distribution With Moderator Gap in Lattice
(C) - Thermal

Figure 2-14. Flux Distribution With Moderator Gap in Lattice.
(C) - Fine Structure

Figure 2-15. Flux Distribution With Cadmium Blade in Gap
(E) - Gold

Figure 2-16. Flux Distribution With Cadmium Blade in Gap
(E) - Dy

Figure 2-17. Flux Distribution With Cadmium Blade in Gap
(E) - Thermal

Figure 2-18. Flux Distribution With Boral Blade in Gap
(F) - Gold

Figure 2-19. Flux Distribution With Boral Blade in Gap
(F) - Dy

Figure 2-20. Flux Distribution With Boral Blade in Gap
(F) - Thermal

Figure 2-21. Flux Distribution With Boral Blade in Gap
(F) - Fine Structure

Figure 2-22. Comparison of Thermal Flux Shapes

3. SMALL LATTICE EXPERIMENTS (TASK 24)

(N. L. Snidow, Task Leader; D. M. Roberts)

3.1. Introduction

The Small Lattice Experiment (SLE), an extension of the epithermal systems of the PCTR¹⁷ technique for k_{∞} and lattice parameter measurements, was developed and tested during the preceding quarter. The test lattice was fueled with 4%-enriched UO_2 rods, had a nonmoderator-to-moderator volume ratio (M/W) of 1.0, and was moderated by a D_2O - H_2O mixture containing approximately 70% D_2O . Measurements of k_{∞} , thermal disadvantage factor, and cadmium ratios of U^{235} and U^{238} in this lattice, in which approximately half of the fissions were epithermal, were in excellent agreement with results obtained from an equivalent critical experiment.⁹

The objective of this program is to apply the SLE technique to the study of two typical SSCR lattices containing thorium as the fertile material. Both lattices have a M/W ratio of 1.0 and are fueled with TUPE fuel rods (93%-enriched UO_2 mixed with ThO_2). The moderator compositions are approximately 70 and 80% D_2O . In each lattice k_{∞} , thermal disadvantage factor, and cadmium ratios of U^{235} and Th^{232} will be measured.

During the reporting quarter preliminary design calculations were performed, and the conceptual design of the experiments was completed. Final drawings for the test insert and void can were prepared and submitted for quotations. Specifications for cutting TUPE rods for the test and end buffer regions were prepared, and the order was placed. Minor modifications to the facility were made.

3.2. Conceptual Design

The major features of the SLE facility, with the exception of the test and buffer regions, are the same as in the first experiments and were described in detail in preceding Quarterly Technical Reports.^{7,9} As illustrated in Figure 3-1, the driver is a graphite honeycomb, fueled with 93%-enriched U-Al foils and graphite bars and mounted on a split-bed assembly. A 2-foot-diameter by 6-foot-high aluminum core tank, containing the buffer and test regions, is mounted in a cavity at the center of the driver. The driver configuration, split-bed assembly and drive system, core tank and moderator system, control rods and drives, and nuclear instrumentation are fully described in the referenced reports.

The core tank contains a central test region (the lattice under study) and a concentric buffer region. The function of the buffer region is to produce a flat and asymptotic spectrum throughout the test region. In the present experiments, the test region is a lattice of 169 (13 by 13) 0.308-inch-OD by 18-inch-long TUPE fuel rods, spaced on a square pitch of 0.387 inch and having an M/W ratio of approximately 1.0. The volume of the test region is approximately one-half of that in the first experiments. Design calculation, confirmed by experience, indicates that adequate sensitivity ($> 50\%$) will be obtained with the smaller volume.

The first SLE measurements demonstrated that a substantial portion of the buffer region can be dissimilar to the test region without seriously increasing the spectral mismatch error in k_{∞} . This is of particular significance when the supply of fuel for the lattice under study is limited. In the present experiments, however, sufficient fuel to make the entire buffer identical to the test region is available. Therefore, the buffer region also consists of TUPE fuel rods spaced on a square pitch of 0.387 inch. Both test and buffer regions are moderated by the same D_2O - H_2O mixture.

3.3. Estimate of Expected Error

In an idealized SLE, k_{∞} of the poisoned test region is exactly unity when a null-reactivity condition exists between the poisoned test and a void. The departure from $k_{\infty} = 1$ for null reactivity under the actual conditions of the experiment represents the error in k_{∞} of the

unpoisoned test due to spectral mismatch. This error was estimated for the present experiments with no poison in the buffer and found to be for this extreme case only 0.8% for 70% D_2O and 0.4% for 80% D_2O . Adding poison to the buffer will reduce this error considerably below this value.

The infinite-medium multiplication factor of the unpoisoned test medium is given by⁹

$$k_{\infty} = \frac{\epsilon}{\epsilon_p} \frac{p}{p_p} \frac{f}{f_p} \frac{(1+\delta_{25})}{(1+\delta_{25})_p} P$$

where the subscript p refers to the poisoned medium, and P is a factor which converts the ratio $(1+\delta_{25})/(1+\delta_{25})_p$ measured in a finite medium to the ratio for an infinite medium. Approximate values and estimated errors for each ratio, calculated using the BPG-2 code, are given in Table 3-1. The error in the ratio p/p_p is based on a 5% error in the calculation of resonance escape from boron. A 1% error in the measured mass of poison for null reactivity and a 2% error in the measured cell flux ratios combined to produce the stated error in f/f_p . The error in the term $(1+\delta_{25})P/(1+\delta_{25})_p$ assumes a precision of $\pm 0.5\%$ in the U^{235} cadmium-ratio measurements and a 50% error in the calculation of $P-1$. On this basis k_{∞} should be measurable to approximately 1% in both experiments.

Table 3-1. Estimate of Potential Error in k_{∞}

Ratio	70% D ₂ O		80% D ₂ O	
	Value	Estimated error in ratio	Value	Estimated error in ratio
ϵ/ϵ_p	0.997	< 0.001	0.998	< 0.001
p/p_p	1.130	0.005	1.117	0.005
f/f_p	1.282	0.006	1.204	0.004
$\frac{(1+\delta_{25})}{(1+\delta_{25})_p} P$	0.852	0.006	0.863	0.008
k_{∞}	1.232	0.012	1.158	0.012

3.4. Design of Buffer and Test Regions

3.4.1. Fuel Rods

The TUPE fuel rods used in the buffer and test regions are 5-foot-long by 0.308-inch-diameter aluminum tubes filled with sintered pellets of blended 93%-enriched UO₂ and ThO₂ ($N_{Th}/N_{25} = .15$). Other properties of the fuel rods are listed in Table 3-2. The fuel rods for the test region, however, are cut to shorter lengths as described in Section 3.4.4.

Table 3-2. Physical Properties of TUPE Fuel Rods

OD, in.	0.308 ± 0.001
Wall thickness, in.	0.014 ± 0.001
Wall material	No. 1100 Al
Fuel diameter, in.	0.260 ± 0.002
Overall length, in.	62.0
Active length, in.	60.0 ± 0.1
Wt of fuel, gm/rod	434.6 ± 0.2
Wt of uranium, gm/rod	25.80 ± 0.02
Wt of U ²³⁵ , gm/rod	24.04 ± 0.02
Wt of ThO ₂ , gm/rod	405.0 ± 0.2
Atoms Th/atoms U ²³⁵	15.00 ± 0.05
Fuel density, gm/cm ³	8.33 ± 0.14

3.4.2. Buffer Region

The fuel rods in the buffer region are fully aligned at the top and bottom and, to a lesser extent, at two midplane locations by egg-crate grid plates. These grid plates are constructed of 0.071-inch-thick by 1-inch-wide aluminum strips that interlock on a 0.387-inch pitch. The bottom grid plate is complete. The top grid plate, however, has every other strip missing, so that four fuel rods can be loaded through each opening. Plugs are inserted in the center of each group of four fuel rods, constraining each rod to a corner location. This arrangement facilitates the loading of the lattice while retaining the accurate spacing so easily obtained with the egg-crate structure.

The two 1-inch-thick intermediate grid plates are located at elevations corresponding to the top and bottom of the test region. Like the top grid plate, these grids are open, i. e., every other strip is missing. However, the strips for separate grids are staggered so that each fuel rod is completely bounded by four strips—on two sides at the upper intermediate grid and on the remaining two sides at the lower intermediate grid. This open arrangement facilitates loading the fuel rods while providing control of rod spacing in the

important area near the test region. The intermediate grid plates do not extend over the entire buffer cross section, but cover only the area around the test insert and along the diameter where flux traverses will be made.

All four grid plates are provided with a 6.6-inch square opening at the center for the test insert. The test insert is guided into position by four aluminum angles (1 in. by 1 in. by 1/16 in.) placed in the corners of the opening and fastened to the top grid plate. This arrangement facilitates the insertion and removal of the test insert and provides accurate alignment and spacing between the fuel rods in the test insert and those in the buffer region.

The four grid plates are aligned and supported by four 3/8-inch-diameter threaded stainless steel rods located at the periphery of the buffer region. Since the TUPE rods are only 5-feet long, the assembly is made axially symmetrical by supporting them on an aluminum shelf approximately 6 inches above the base of the tank.

The arrangement of the internal structures is illustrated in Figures 3-2 and 3-3. Figure 3-4 shows the internal structure before assembly and final alignment in the core tank.

3.4.3. Test Insert

The test insert is an assembly of (17 by 17) TUPE fuel rods, 6.58-inches square by 62-inches long, that fits in the square hole in the center of the buffer region. The outer two rows form part of the buffer and are included with the test insert to insure that the lattice spacing in the vicinity of the test region is accurately maintained. The upper and lower 22-inch sections serve as axial portions of the buffer, and the central 18-inch section contains the test region. The lattice pitches in all regions are the same, i. e., 0.387 inch.

The test insert is held together by four 0.25-inch-diameter stainless steel tie rods, which replace the corner TUPE fuel rods. The remaining 116 rods in the outer two rows are full-length TUPE rods. The 169 short fuel rods in each of the end buffer regions are cut from TUPE rods and sealed with epoxy-cemented aluminum end plugs. The cut rods in the end buffer regions are supported by thin (1/4- to 1/2-in. thick) stainless steel grid plates, which extend outward to include the

two rows of full-length TUPE rods and the four tie rods.

3.4.4. Test Region and Void Can

The test region itself is a sublattice of 169 (13 by 13) cut TUPE fuel rods, 5.031-inches square by 18-inches long, held at the top and bottom by aluminum grid plates, 5/16- and 1/2-inch thick, respectively. The test region is removable as a unit without disassembling the test insert by withdrawing the full-length TUPE rods on one side of the test insert and moving the test region through this opening.

In the measurement of k_{∞} , the reactivity difference between the poisoned test region and a void occupying the same volume is determined. Since the moderator is liquid, the void is simulated by a thin-wall aluminum can. Strength considerations require a wall thickness of at least 1/8 inch, and the hazard of flooding is reduced by dividing the can into six leak-tight internal compartments with 0.081-inch-thick aluminum partitions. The outer dimensions of the void can, 5.031-inches square by 18-inches long, exactly match those of the test region. Although nitrogen absorptions in the air inside the void can are negligible, a small correction for the aluminum will be obtained from comparative reactivity measurements on similar void cans containing a larger fraction of aluminum.

3.4.5. Poisons

The test region will be poisoned with the binal foils used in the first experiments. Binal is a homogeneous mixture of B_4C and aluminum that contains 2.53 wt % natural boron and has a density of 2.62 gm/cm³. The foils are 0.010-inch thick by 3-inches wide. To flatten the flux across the poisoned test region, poison is also added to the buffer region. This is done by taping 0.050-inch-diameter silver (90% Ag-10% Cu) wires to the buffer TUPE fuel rods. Calculations indicate that two wires per rod will be required. The wires will be located in the open spaces between the rods and the corners of the egg-crate grid plates.

Figure 3-1. Facility for Small Lattice Experiments

Figure 3-2. Test and Buffer Regions - Horizontal Section

Figure 3-3. Test and Buffer Regions - Vertical Section

Figure 3-4. View of Internal Structure

4. THEORETICAL SUPPORT (TASK 25)

(H. S. Barringer, Task Leader; K. E. Roach,
D. H. Roy, W. R. Worley, N. Vutz)

4.1. Development of the RIP Program

A method for describing near-thermal, resonance, and high-energy absorption for use in multigroup spectrum and criticality codes (in particular the BPG code developed for this program) has been developed. For a specified absorber the cross section in the near-thermal region (up to the energy of the first resolved peak) is treated as $1/v$. In the resolved-resonance region corrections are applied for Doppler broadening and the use of the rational approximation for the escape probability in heterogeneous calculations. Both the narrow resonance (NR) and narrow resonance infinite absorber (NRIA) approximations are available. The NR approximation is applied in the unresolved range with the Doppler coefficient averaged over the Porter-Thomas distribution of reduced neutron channel widths. Smooth cross-section data are used in the region above the unresolved resonance cutoff.

The method has been programmed in Fortran language for use on the Philco 2000 computer. The program package, entitled RIP-Resonance Integral Program, contains subroutines for averaging cross sections over an arbitrary structure, calculating the resonance integral for a set of resolved peaks, and calculating L-factors for input to MUFT, PLMG, and P3MG programs.

For a specified absorber, the RIP program treats absorption in four distinct energy ranges:

RANGE 1. From the thermal cutoff to the energy of the first resolved resonance peak, the absorption cross section is treated as $1/v$. Assuming a $1/E$ flux spectrum, the average cross section for groups in this range is then given by

$$\bar{\sigma}_a = \frac{2 \sigma_a(E)^* \sqrt{E}^*}{\ln \frac{E_{i+1}}{E_i}} \left[\frac{1}{\sqrt{E_i}} - \frac{1}{\sqrt{E_{i+1}}} \right] \quad (4.1)$$

where $\sigma_a(E^*)$ = thermal cross section at 0.0253 ev

E_i, E_{i+1} = lower and upper group bounds, respectively.

RANGE 2. In the resolved-resonance region, Wigner's approximation for the resonance escape probability is used to obtain the effective resonance integral for a narrow, isolated peak. For any specified absorber, the peaks are assumed to be widely separated, with a constant-lethargy-dependent collision density existing between the peaks. With these assumptions, the effective resonance integral for a peak is given by

$$I = \int_{\text{peak}} \frac{\sigma_a^{(F)}(u)}{1 + \frac{1}{\sigma_p} \left[\sigma_a^{(F)}(u) + \sigma_{sr}^{(F)}(u) + \sigma_{si}^{(F)}(u) \right]} du \quad (4.2)$$

where

$\sigma_a^{(F)}, \sigma_{sr}^{(F)}, \sigma_{si}^{(F)}$ = resonance-absorption, resonance-scattering, and interference-scattering cross sections, respectively.

Both the NR and NRIA approximations are available in either homogeneous or heterogeneous resonance-integral calculations. RIP uses, therefore, four expressions for the σ_p term given in Equation 4.2.

$$\sigma_p^{(1)} = \sigma_p^{(F)} + \frac{1}{N_F} \sum_{i \neq F} N_i \sigma_s^{(i)} \quad \text{NR - homogeneous}$$

$$\sigma_p^{(2)} = \frac{1}{N_F} \sum_{i \neq F, j} N_i \sigma_s^{(i)} \quad \text{NRIA - homogeneous}$$

$$\sigma_p^{(3)} = \sigma_p^{(F)} + \frac{1}{N_F} \sum_{i \neq F} N_i \sigma_s^{(i)} + \frac{1}{N_F \bar{S}^*} \quad \text{NR - heterogeneous}$$

$$\sigma_p^{(4)} = \frac{1}{N_F} \sum_{i \neq F, j} N_i \sigma_s^{(i)} + \frac{1}{N_F \bar{S}^*} \quad \text{NR1A - heterogeneous}$$

where

$\sigma_p^{(F)}$ = potential scattering cross section of absorber

$\bar{S}^*$ = effective chord length of lump

N_F = number density of absorber

$N_i \sigma_s^{(i)}$ = number of density and scattering cross section of elements in the lump or mixture

index j = elements for which the maximum energy loss in scattering is less than the practical width of the resonance peak.

Doppler-broadening correction factors are obtained numerically from a 1056-entry table compiled from the work of Dresner, Nordheim, and Nather. For heterogeneous calculations, a modified form of Rothernstein's correction for use of the rational approximation to the escape probability is applied. Interference between potential and resonance scattering in the absorber is neglected. The effective resonance integral for a peak is then given by

$$I = \frac{\sigma_p^{(i)} \Gamma_Y}{E_0} J(\theta, \beta)$$

$i = 1$ for NR - homogeneous

$= 2$ for NR1A - homogeneous

$$I = \frac{\sigma_p^{(i)} \Gamma_Y}{E_0} J(\theta, \beta) + \Delta I_G^{(i)}$$

$i = 3$ for NR - heterogeneous

$= 4$ for NR1A - heterogeneous

where

$J(\theta, \beta)$ = Doppler-broadening function

E_0 = energy of peak

$\Delta I_G^{(i)}$ = correction for use of rational escape probability.

The total resonance integral for a group is the sum of the resonance integrals for the resolved peaks lying within the group bounds.

RANGE 3. For a given energy within a group in the unresolved resonance region, the Doppler-broadening function is averaged over the statistical distribution of neutron widths as given by Porter and Thomas. An integration over energy between the group bounds using the NR approximation is then performed to yield the following form of the resonance integral for a group:

$$I = \frac{\sigma_p^{(i)} \Gamma_Y}{D} \int_{E_i}^{E_{i+1}} \frac{dE}{E} \frac{1}{\sqrt{2\pi}} \int_0^\infty \frac{e^{-y/2}}{\sqrt{y}} J[\theta(y), \beta(y)] dy$$

where

$$y = \frac{\Gamma_n^0}{\langle \Gamma_n^0 \rangle}, \text{ the normalized, reduced neutron width}$$

D = average level spacing.

Averaging of the Doppler-broadening function and integration over the group is performed numerically using a ten-point Laguerre-Gauss quadrature formula and a four-point Newton-Cotes formula, respectively.

RANGE 4. In the region above the unresolved resonances, designated the high energy region, smooth absorption cross sections (either point data or group cross sections) are assumed to be available. The resonance integral for groups in this region is the infinitely dilute value obtained by integrating the cross section over the group.

The limits for the specified ranges are arbitrary. All four ranges are included in order that a complete resonance-absorption distribution function, i.e., a ψ -set, may be computed for input to BPG,

a one-dimensional multigroup code which solves the transport equation in the B_1 or P_1 approximations. This ψ -set describes the smooth absorption cross section in the $1/v$ and high energy regions and the fractional resonance absorption for each group in the resolved and unresolved regions.

In the MUFT and PIMG codes a homogeneous, non-Doppler broadened treatment of resonance absorption is available. In order to correct this approach for practical application of the codes, provision is made for modifying this treatment with the use of L-factors, which essentially divide-out the code-generated resonance integral and allow the insertion of the correct region, element, group, and peak-dependent resonance integral. Assuming one pseudo-resonance peak in each group in which resonance absorption occurs, RIP computes the group, element, and region dependent L-factor yielding the correct effective resonance integral in MUFT and PIMG calculations. The pseudo-resonance peak is chosen to permit a single library tape for these codes for a particular design problem, and cases involving changes in temperature, geometry, element compositions and concentrations may be prepared by inserting the appropriate L-factors on cards.

In addition to the ψ -set and L-factor calculations, RIP contains subroutines which allow the averaging of up to 400 cross-section data points over an arbitrary multigroup structure and the calculation of the effective resonance integral for up to 100 separately designated resonance peaks in the manner discussed for Range 3.

4.2. Analysis of Lattice Perturbations at 72% D_2O

Two-dimensional (PDQ) calculations have been completed for the following lattice perturbations:

1. Flat moderator gap.
2. Flat boral blade in gap.
3. Flat boral blade, no gap.
4. Flat cadmium blade in gap.
5. Flat aluminum follower in gap.
6. Cruciform boral rod in cruciform gap.

The two-dimensional results are presently under analysis and will be reported at a later date in comparison with experiments.

Coefficient data for the PDQ cases (four energy groups) was taken from the BPG-II code for all materials and energies except the thermal (fourth) group of the boral and cadmium plates. The control-rod materials were treated as being black to thermal neutrons. All cases were calculated at a moderator height of 111 cm and a D₂O concentration of 72.4 mole per cent.

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