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MASTER

SPECTRAL SHIFT CONTROL REACTOR
BASIC PHYSICS PROGRAM

Measurement and Analysis of Perturbed Lattices
of Slightly Enriched UO_2
Moderated by D_2O - H_2O Mixtures

October 1963

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THE BABCOCK & WILCOX COMPANY
NUCLEAR DEVELOPMENT CENTER

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ABSTRACT

Critical experiments and theoretical calculations of reactivity and flux perturbations were done as a part of the Spectral Shift Control Reactor Basic Physics Program. During the current phase of the program, three major critical assemblies were studied; the basic cores had 1.206-cm diameter, aluminum clad, 2.46%-enriched UO_2 fuel rods on a square lattice pitch of 1.511 cm. Moderator compositions for the three major cores had 0, 50, and 72 mole % D_2O . Boric acid was added to keep the core radius constant at 61.11 cm. Data on a zone-loaded core studied under an earlier contract were also included in this report. This assembly had an inner zone of 93%-enriched aluminum clad UO_2 - ThO_2 fuel rods surrounded by an outer zone of 4%-enriched stainless steel clad UO_2 fuel rods. The moderator composition was 81% D_2O .

Perturbers were introduced axially by removing fuel pins to create moderator gaps and by inserting perturbing blades and cruciform rods. The blades were 10 inches wide. The cruciform rods were 6 inches from tip to tip. The materials were Boral, cadmium, or aluminum. Most perturbers were fully inserted, but some measurements were made while the Boral cruciform rod was 1/3 and 2/3 withdrawn.

Thermal flux distributions were measured with gold and dysprosium foils. Reactivity was determined by using $\partial\rho/\partial h$ techniques and by measuring the differential boron worth and the boron concentration required for criticality at the reference moderator height.

Reactivity and thermal neutron flux shapes were calculated using PDQ-4, a four-group, two-dimensional neutron diffusion code for the Philco 2000 computer, and TKO, a four-group, three-dimensional code for the IBM-704 computer.

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1. INTRODUCTION

1.1. SSCR Basic Physics Program

In July 1960, The Babcock & Wilcox Company (under AEC contract) initiated a study of the basic physics underlying the Spectral Shift Control Reactor (SSCR) concept. In application, the reactor core is a lattice of slightly enriched uranium (or thorium) oxide rods, moderated and cooled by a variable mixture of light and heavy water. Initially, the moderator is rich in heavy water, so the neutron spectrum is quite epithermal, and a relatively large fraction of the excess neutrons are absorbed in the fertile material. As fuel is consumed, the moderator is diluted with light water, thereby shifting the spectrum towards thermal energy and providing the necessary increase in core reactivity.

The objective of the SSCR Basic Physics Program is to study the nuclear properties of rod lattices moderated by D_2O - H_2O mixtures in the range of application to the SSCR concept. Primary emphasis is given to the uranium cycle having U^{235} enrichments from 2 to 4%. Moderator compositions extend from 0% D_2O (light water) to about 90% D_2O , and the nonmoderator-to-moderator volume ratio (M/W) is in the range of 0.7 to 1.2. The experimental program includes uniform and perturbed lattice critical experiments, exponential experiments at room and elevated temperatures, and neutron age measurements. The theoretical program includes the development of analytical methods applicable to SSCR-type lattices and the analysis and correlation of the experimental results.

This report summarizes the experimental results and the analysis of perturbed and other nonuniform lattice critical experiments. The results of the first-phase uniform lattice critical experiments, exponential experiments, and age measurements have already been reported¹⁻⁶, and a topical report summarizing all of the uniform lattice experiments and their analysis will soon be issued⁷. Additional details

on all phases of the program are available in the series of SSCR Basic Physics Program Quarterly Technical Reports⁸⁻¹⁷.

1.2. Perturbed Lattice Experiments

Although the study of uniform lattice properties was emphasized, a few perturbed or nonuniform lattice experiments were included to provide data on some of the special features necessary for the design of practical power reactors operating on the spectral shift principle. No attempt was made to assemble exact mock-ups of these reactor complexities, however. Rather, the perturbations were introduced in fairly simple geometries to test specific features of the theoretical model and to provide a normalized basis for extending the calculations to a specific reactor design.

1.2.1. Zone-Loading

A power reactor operating on the spectral shift principle will probably be zone-loaded into regions of different enrichments to flatten the power distribution. Therefore, theoretical methods must predict not only the asymptotic properties of each zone but also the important transition regions between zones where the spectrum is non-asymptotic. Experimental data from the uniform lattice experiments were available to test asymptotic calculations, and nonasymptotic effects were studied in a separate zone-loaded critical assembly.

The zone-loaded assembly (Core VII) consisted of an inner Zone A of 93%-enriched $\text{UO}_2\text{-ThO}_2(\text{N}_{\text{Th}}/\text{N}_{25} = 15)$ fuel rods surrounded by an outer Zone B of 4%-enriched UO_2 fuel rods. The M/W ratio in each zone was approximately 1.0, and the moderator composition was 81% D_2O . The fuel was selected on the basis of availability, and the dissimilarity between the zones was deliberately emphasized to test analytical methods as rigorously as possible rather than to mock-up a specific power reactor configuration. The critical conditions, asymptotic properties in each zone, and detailed flux and power distributions were measured.

1.2.2. Blade and Gap Effects

The effects on reactivity and flux distribution of Boral, cadmium, and aluminum blades and of moderator gaps located in a

uniform lattice were measured to provide normalizing data on shutdown blade worth and power peaking around blade channels and fuel elements. The uniform, unperturbed lattice consisted of 2.46%-enriched UO_2 fuel rods at $M/W = 1.0$, and the measurements were obtained at three moderator compositions (72, 50, 0% D_2O) to determine the change over the lifetime of a core. Since the reactivity worth of perturbations is strongly affected by core size, the latter two moderators were borated to keep the core diameter constant in all three cases.

The perturbations introduced into the center of each of the three cores are in the following list. Reactivities were measured for each case, and midplane flux distributions were measured for those cases marked with an asterisk (E and G only at 72% D_2O).

- *A - Unperturbed uniform lattice
- *B - Boral blade in uniform lattice
- *C - Moderator gap produced by removing row of fuel rods
- D - Aluminum blade in C
- *E - Cadmium blade in C
- *F - Boral blade in C
- *G - Boral cruciform perturber in gap
- H - Aluminum cruciform perturber in gap

1.2.3. Partially Inserted Rod

Although the SSCR concept does not require control rods for gross reactivity holddown, a small rod is used for power level changes. The effect of a partially inserted rod on power distribution was measured in the uniform lattice having 2.46%-enriched UO_2 , $M/W = 1.0$, and 72% D_2O . Four settings of a Boral cruciform rod were studied: full in, 1/3 out, 2/3 out, and full out. The moderator was borated slightly to keep the critical moderator height constant in all cases. Radial and axial flux distributions and reactivity worths were measured.

1.3. Facility

The experiments were performed in Bay No. 2 of the Babcock & Wilcox Company Critical Experiment Laboratory using a conventional tank-type facility modified for heavy water use. Figure 1-1 shows the 5-foot diameter by 6.5-foot high aluminum core tank mounted inside

an existing 9-foot diameter tank. (The external paraffin reflector was not used in these experiments.) The smaller tank, in which the assemblies were erected, minimized heavy water inventory and was hermetically sealed to control moderator degradation by light water vapor in the atmosphere.

The critical assemblies were provided with four or more 6- to 8-inch-wide safety blades that were thin enough to pass between rows of fuel rods without interrupting lattice pitch regularity. The blades usually were cadmium backed with stainless steel, but Boral was used in the more epithermal lattices. All safety blades were normally fully withdrawn from the core during operations, and criticality was achieved by adjusting the moderator level, moderator composition, or core diameter. Additional details on the design of the facility, moderator addition system, and instrumentation and control system are given in the facility hazards reports^{18,19}.

1.4. Supporting Calculations

The reactivity worths and thermal neutron flux shapes transverse to the perturbations were calculated using the PDQ-4 computer code for the Philco 2000 computer, which solved four-group two-dimensional neutron diffusion equations.

For the partially inserted cruciform rod, code TKO, a three-dimensional four-group neutron diffusion code for the IBM-704 computer, was used to calculate axial thermal flux shapes and k_{eff} .

Figure 1-1. External View of Core Tank

2. ZONE-LOADED ASSEMBLY

2.1. Description

The zone-loaded assembly (Core VII) consisted of an inner square Zone A of 93%-enriched $\text{UO}_2\text{-ThO}_2$ ($N_{\text{Th}}/N_{235} = 15$) fuel rods surrounded by an outer Zone B of 4%-enriched UO_2 fuel rods, as shown in plan and elevation in Figures 2-1 and 2-2. The safety blades shown in the top view of Figure 2-3 were fully withdrawn from the core during operations.

The fuel rods were supported at the top and bottom by egg-crate grid plates consisting of 1-inch-wide slotted aluminum strips interlocked to form a square matrix. In the inner zone, the strips were 0.072 inch thick and were spaced on 0.387-inch centers; in the outer zone, the thickness and spacing were 0.114 inch and 0.595 inch, respectively. Therefore, the M/W ratio was approximately 1.0 in each zone. Since the inner zone, a square matrix of 52 by 52 (20.124 inches square) $\text{UO}_2\text{-ThO}_2$ fuel rods, occupied a square hole formed by the removal of 34 by 34 (20.230 inches square) outer zone rods, an extra 0.053-inch-wide moderator channel was created between the two zones. A thin, drilled midplane grid plate was also provided to improve fuel rod alignment.

2.2. Fuel Rods

The physical properties of the fuel rods are summarized in Table 2-1, where the uncertainties are standard deviations of the mean obtained from vendor quality-control data and check measurements on 50 to 100 randomly selected samples. The impurities are stated as the summation of $N_i\sigma_i$, where N_i is the concentration per cm^3 of oxide fuel. Additional details are given in Reference 3 for the outer rods and References 20 for the inner rods.

Table 2-1. Physical Properties of Fuel Rods

Property	93%-Enriched UO ₂ - ThO ₂	4%-Enriched UO ₂
Fabrication	Pelletized	Swaged
Outer diameter, in.	0.308 ± 0.001	0.4755 ± 0.0015
Wall thickness, in.	0.014 ± 0.001	0.0160 ± 0.0005
Wall material	#1100 Aluminum	#304 SS
Fuel diameter, in.	0.260 ± 0.002	0.444 ± 0.002
Total length, in.	62.0 ± 0.2	≈ 71.5
Active (fuel) length, in.	60.0 ± 0.1	66.7 ± 0.3
Weight of fuel, gm/rod	434.6 ± 0.2	1600 ± 2
Weight of U/wt UO ₂ , %	- -	88.01 ± 0.02
Weight of ThO ₂ , gm/rod	405.0 ± 0.2	- -
Weight of U ²³⁵ , gm/rod	24.04 ± 0.02	56.61 ± 0.10
Enrichment, wt 25/wt U, %	- -	4.020 ± 0.005
Atoms Th/atoms U ²³⁵	15.00 ± 0.05	- -
Bulk fuel density, gm/cm ³	8.33 ± 0.14	9.46 ± 0.10
Σ _a (impurities), cm ² /cm ³ oxide	<6 × 10 ⁻³	<5 × 10 ⁻⁴

2.3. Critical Parameters

The critical parameters of the zone-loaded assembly are summarized in Table 2-2. The effective core radius, the radius of the outer zone, was computed from the relation

$$\pi R^2 = (\text{Number of rods}) (\text{Pitch})^2$$

where the equivalent number of outer zone rods necessary to fill the inner zone are included. The moderator height was measured relative to a reference plane at the bottom of the fuel in the inner zone (see Figure 2-2) by a manometer and a calibrated conductivity probe. The concentration of D₂O in the moderator was derived from precise density measurements in calibrated pycnometers³; no evidence of moderator degradation was found by comparing first and last day samples. The assembly was reflected in the radial direction by 8.16 cm of moderator plus the 0.5-inch-thick aluminum core tank wall. The axial reflector was complex because of the difference in length of the two types of fuel rods.

Table 2-2. Critical Parameters of Core VII

<u>Parameter</u>	<u>Inner Zone A</u>	<u>Outer Zone B</u>
Type of fuel	UO ₂ - ThO ₂	4% UO ₂
Number of fuel rods	2704	5212
Fuel rod diameter, in.	0.308 ± 0.001	0.4755 ± 0.0015
Lattice pitch, in.	0.387 ± 0.001	0.595 ± 0.001
M/W ratio	0.990	1.006
Total mass U ²³⁵ , kg	65.0	295.1
	<u>Both zones</u>	
Effective radius, cm	68.04	
Moderator composition, mole % D ₂ O	81.2 ± 0.1	
Critical moderator height, cm	141.3 ± 0.1	
∂ρ/∂h at 141.3 cm, g/cm	4.03 ± 0.20	
Temperature, C	20 ± 1	

2.4. Thermal Flux Distribution

2.4.1. Radial Distribution

The thermal flux distribution in the midplane of Core VII was mapped with bare 0.259-inch-diameter by 0.007-inch-thick Dy-Al (≈ 5 wt% Dy) foils. The foils, spaced every two lattice pitches, were mounted on 3/4-inch-wide by 0.005-inch-thick steel foil holders located between fuel rods at an elevation of 73 cm above the reference plane. Traverses were made along several parallel lines. No. 1 was along the core diameter; the other traverses were parallel to this one, but were separated by several rows of fuel rods as specified in the following list:

No. 1:	0 lattice pitches =	0.00 cm
No. 2:	9 lattice pitches =	13.60 cm
No. 3:	13 lattice pitches =	19.65 cm
No. 4:	17 lattice pitches =	25.69 cm
No. 5:	19 lattice pitches =	28.71 cm
No. 6:	24 lattice pitches =	36.27 cm
No. 7:	32 lattice pitches =	48.36 cm

After irradiation, the foils were beta counted using an automatic sample changer and a scintillation counter with a thin anthracene crystal. This device was controlled by a master foil counter, which automatically increased the counting time as the foils decayed. Each foil was counted two or three times for a total count of at least 10,000. The foil activities were corrected for small variations in dysprosium content by irradiating the foils on a wheel in a constant flux and measuring relative activities. All traverses were internormalized by using four Dy-Al monitor foils.

One traverse across the core was made with cadmium-covered foils to determine whether the fraction of epithermal activity changed significantly. The cadmium ratio was 5.6 at the center of the core and increased to a maximum of 6.7 at the outer edge. Over most of the core, the epithermal fraction varied by less than 3%; so bare foil data were considered representative of the thermal flux.

The normalized activities from the seven traverses are shown in Figure 2-4. Figure 2-5 is a two-dimensional flux plot constructed from these traverses assuming symmetry. The flux values, accurate to about $\pm 2\%$, were taken at 2 cm intervals from the smooth

curves of Figure 2-4. These curves were drawn to force agreement at intersecting points, but were never adjusted beyond the limits imposed by the standard deviations of the data.

2.4.2. Axial Distribution

Axial flux measurements were made using cadmium-covered 0.259-inch-diameter by 0.005-inch-thick gold foils spaced at 5-cm intervals. The traverse through the inner zone was made along the core axis using a thin steel foil holder. The traverse through the outer zone was made in the test insert position using a 1/16-inch-thick by 1-inch-wide lucite foil holder. Experiments in other cores showed that both types of foil holders gave equivalent results⁷. The foils were counted in the same way as the Dy-Al foils.

Axial bucklings were derived from least square fits of the data in the asymptotic region (15 to 125 cm). Although the results given in Table 2-3 agree within their combined standard deviations, the difference can be attributed to the longer fuel rods in the outer zone. The axial reflector savings are based on the critical moderator height of 141.3 cm.

Table 2-3. Axial Buckling and Reflector Savings (Core VII)

	<u>Inner zone</u>	<u>Outer zone</u>
$B_z^2, \times 10^{-4} \text{ cm}^{-2}$	3.88 ± 0.03	3.82 ± 0.06
$\delta_z, \text{ cm}$	18.2	19.5

2.5. Fission Distribution

The radial U^{235} fission distribution in the midplane of Core VII was measured using bare and cadmium-covered foils of 93%-enriched U-Al ($\approx 18 \text{ wt}\% \text{ U}$). The foils were 0.259 inch in diameter by 0.010 inch thick; the cadmium covers were 0.020 inch thick. The foils were spaced every two lattice pitches, located in the moderator between fuel rods, and held on thin (0.005 inch) steel foil holders. Four U-Al monitor foils were used to normalize the bare and cadmium-covered runs.

In each run the foils were irradiated for 20 minutes at a constant power level of several hundred watts with all control blades withdrawn. After a downtime of at least 30 minutes, each foil was counted for two 1-minute periods on a sodium iodide scintillation spectrometer biased so that only photons above 200 kev were counted. Count rates were at least 15,000 counts/min. The foils in comparable bare and cadmium-covered runs were counted in the same sequence and at the same times after shutdown. The ratio of bare-to-cadmium-covered data foil activities was computed at each counting time, and the ratios were averaged. The same procedure was followed for each U-Al monitor foil. These ratios did not appear to vary systematically with time; so the cadmium ratio was obtained by dividing the average data foil activity ratio by the average monitor foil activity ratio. The foils were not calibrated for uranium content, but they were corrected for background. Since the same foils were used in the same positions in the bare and cadmium-covered runs, the cadmium ratios should be correct, but slight variations in the uranium content contribute to the scatter in the power distribution.

The results are shown in Figure 2-6, where the accuracy of the data is about $\pm 2\%$. The cadmium ratios of U^{235} in the moderator in the asymptotic region of each zone are:

$$C_{25} = 1.98 \pm 0.02 \text{ (inner zone)}$$

$$C_{25} = 2.08 \pm 0.02 \text{ (outer zone)}$$

Both results compare favorably to those derived from the U^{235} cadmium ratio in the fuel and the thermal disadvantage factor⁷.

Figure 2-1. Core VII - Horizontal Section

Figure 2-2. Vertical Dimensions of Zone-Loaded Core VII

Figure 2-3. Core VII Photograph

Figure 2-4. Radial Thermal Flux Distribution in Core VII

Figure 2-5. Midplane Thermal Flux Distribution in Core VII

Figure 2-6. Radial Fission Distribution in Core VII

3. BLADE AND GAP EFFECTS (Uniform Lattices)

3.1. Description of Cores

The effects on reactivity and flux distribution of several blade and gap perturbations were measured in three uniformly loaded cores which differed only in moderator composition. Core XVIII was moderated by an unpoisoned D_2O - H_2O mixture of 72.1 mole % D_2O ; Cores XIX and XX were moderated by approximately 50% D_2O and 0% D_2O , respectively, and were borated to keep the core diameter constant.

The cores were assembled in the 5-foot diameter aluminum core tank using 1-inch-thick aluminum egg-crate type grid plates at the top and bottom and two 1/16-inch-thick drilled aluminum sheets for additional alignment near the midplane as shown in Figure 3-1. The fuel rods were spaced on a square lattice pitch of 0.595 inch; so the nonmoderator-to-moderator volume ratio M/W was 1.001. Figure 3-2 is a horizontal section through the unperturbed lattice showing the positions of the peripheral fuel rods and the direction and extent of the flux traverses. Note that the geometrical center of the core is a fuel rod. Figure 3-3 is a top view of the core with a cruciform perturber in place. The flat control blades were fully withdrawn from the core during all measurements.

The fuel rods were 5-foot long by 0.475-inch OD aluminum tubes filled with sintered pellets of 2.46%-enriched UO_2 . Other properties of the fuel are listed in Table 3-1, where the uncertainties are standard deviations of the mean obtained from vendor quality control data and check measurements on 50 to 100 randomly selected samples. The impurities are given as the summation of $N_i \sigma_i$, where N_i is their concentration per cm^3 of UO_2 . Additional details are available in Reference 15.

The critical parameters of the unperturbed cores are summarized in Table 3-2. The equivalent core radius was computed from the relation $\pi R^2 = Np^2$, where N is the number of fuel rods and p is the lattice pitch.

Table 3-1. Properties of 2.46%-Enriched UO_2 Fuel Rods

Property	Value
Outer diameter, in.	0.4748 ± 0.0006
Wall thickness, in.	0.032 ± 0.001
Wall material	#6061 Aluminum
Pellet diameter, in.	0.4054 ± 0.0005
Total length, in.	61.59 ± 0.16
Fuel length, in.	60.37 ± 0.35
Weight of UO_2 , gm/rod	1306 ± 1
Weight of U/wt UO_2 , %	88.13 ± 0.01
Weight of U^{235} /wt U, %	2.459 ± 0.002
Bulk UO_2 density, gm/cm^3	10.24 ± 0.04
Σ_a (impurities), $\text{cm}^2/\text{cm}^3 \text{UO}_2$	$<4 \times 10^{-4}$

Table 3-2. Critical Parameters of Unperturbed Cores XVIII-XX

Parameter	Core XVIII	Core XIX	Core XX
Number of fuel rods	5137	5137	5137
Enrichment, wt%	2.46	2.46	2.46
Core radius, cm	61.11	61.11	61.11
Reflector thickness, cm	15.1	15.1	15.1
Moderator height, cm	107.9	97.7	93.2
Mole % D_2O	72.1	50.0	0.0
gm B/l	0.0	0.778	1.675
Lattice pitch, cm	1.511	1.511	1.511
Rod diameter, cm	1.206	1.206	1.206
M/W ratio	1.001	1.001	1.001
Temperature, C	20	21	23

The radial reflector thickness is the difference between the inner radius of the core tank and the core radius. All control blades were fully withdrawn when the critical moderator height, relative to the bottom of the active fuel, was measured with a manometer to an accuracy of at least ± 0.1 cm.

The concentration of D_2O in the moderator was derived from precise density measurements in calibrated pycnometers³. The measurements had a precision of about $\pm 0.03\%$, but the absolute accuracy is conservatively estimated to be $\pm 0.1\%$ in D_2O concentration. Some evidence of moderator degradation at the highest D_2O concentration was observed by comparing analyses before and after each set of experiments, but the total change was within the limits quoted. The D_2O concentrations do not include the hydrogen in the boric acid.

In some of the cores, boric acid (H_3BO_3) was dissolved in the moderator. The boron concentration, given as grams of natural boron per liter of moderator (gm B/l) was determined by potentiometric titration with KOH.³ The KOH was normalized against standard solutions of both boric acid and potassium hydrogen phthalate, which agreed to within about 0.3%. The validity of the procedure for D_2O - H_2O mixtures was confirmed by analyzing standard samples. The precision of the analyses was 0.3%, and the absolute accuracy was about 0.5%.

3.2. Description of Perturbers

The dimensions and locations of the perturbers that were introduced into the uniform lattices are given in Table 3-3 and Figure 3-4. The unperturbed uniform lattice is designated as Loading A. In Loading B, a 10-inch-wide Boral blade was inserted in the uniform lattice between two rows of fuel rods, 0.5 lattice pitch from the center of the core. Seventeen fuel rods along the diameter of the core were removed to create the moderator gap, Loading C. In Loadings D, E, and F, 10-inch-wide aluminum, cadmium, or Boral blades were inserted in the center of the gap. Loadings G and H were formed by removing 21 fuel rods from the center of the core and inserting 6-inch-wide Boral or aluminum cruciform rods in the center of the gap. All perturbers extended from 1 inch above the bottom of the fuel to several inches above the top of the fuel.

Table 3-3. 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)		17 rods	1 rod
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 rod	Boral	6.00 ± 0.04	0.093 ± 0.002
H	Cruciform rod	Aluminum	6.02 ± 0.03	0.090 ± 0.001

The aluminum blade (D) and cruciform rod (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 stainless steel (#304) sheets with 0.003-inch-thick Mylar adhesive tape. Boral is a mixture of natural boron carbide (B_4C) and aluminum, clad on both sides with aluminum. The meat is approximately 35 wt% boron carbide; boron carbide is 75.5 wt% boron; the aluminum in the meat and cladding is commercially pure and has a density of 2.70 gm/cm^3 . Boron analyses were performed on samples cut from each end of each Boral piece. Although the meat thickness and gm B/cm^2 varied appreciably, the deduced meat density was constant within 2% for all samples, indicating that the chemical analyses were correct to at least this degree.

The compositions of the Boral blades and rod are listed in Table 3-4, where the uncertainties represent the difference between the top and bottom samples. Although the four parts of the cruciform rod differ substantially, the difference can easily be taken into account in the calculations if necessary. However, all four parts of the cruciform rod are black to thermal neutrons; so the differences should affect only the epithermal component. Therefore, the calculational error introduced by the assumption that the cruciform rod is symmetrical, i.e., the composition of each of the four parts equals the weighted average composition, should be quite small. This was confirmed in Core XIX by comparing the reactivity of Blade F, which had about 10% less boron,

in the same loading as Blade B and finding a 2.2% reduction in blade worth. In Core XX, the reduction was about $(3.7 \pm 1.5)\%$.

Table 3-4. Composition of Boral Blades and Rod

Loading	Thickness, mils		Meat density, gm/cm ³	Boron thickness, gm B/cm ²
	Total	Meat		
B	97 ± 2	68 ± 1	2.28 ± 0.02	0.105 ± 0.002
F	93 ± 2	61 ± 4	2.30 ± 0.07	0.094 ± 0.008
G-north	89 ± 1	45 ± 3	2.34 ± 0.01	0.070 ± 0.005
G-south	92 ± 1	59 ± 2	2.27 ± 0.01	0.090 ± 0.003
G-east	96 ± 1	64 ± 1	2.31 ± 0.04	0.100 ± 0.001
G-west	96 ± 1	64 ± 1	2.31 ± 0.04	0.100 ± 0.001
G-avg	93 ± 2	58 ± 3	2.30 ± 0.02	0.090 ± 0.007

3.3. Reactivity Measurements

The reactivity worths of the perturbors were measured two ways to permit a comparison of techniques. In the first method, the critical moderator height was measured for each loading without changing the moderator composition, and the excess reactivity was determined from the integral of $\partial\rho/\partial h$. Measurements of $\partial\rho/\partial h$ were made at each loading by standard techniques. Errors due to deuterium photoneutrons were minimized by separating runs by several hours and by disregarding period data during the first few decades. Periods were converted to reactivities using an inhour relation computed for each core. Changes in moderator level were measured with a remotely operated conductivity probe, accurate to at least ± 0.05 cm. Figure 3-5 gives $\partial\rho/\partial h$ as a function of the average moderator height and the integral of $\partial\rho/\partial h$ vs h relative to 145 cm. Figure 3-6 is a plot of the same data correlated against $(\partial\rho/\partial h)^{-1/3}$. These results are for Core XVIII; similar data were obtained for Cores XIX and XX.

In the second method, the reactivity worth of each perturber was obtained by measuring the differential boron worth and the concentration of boron required to raise the critical moderator height to a common

level, arbitrarily chosen to be 145.0 cm. Boron concentrations were measured by the procedure described in Section 3.1. Although the two methods are not truly independent (both rely basically on $\partial\rho/\partial h$ data), the results show that there are no gross systematic errors in either technique.

The results are summarized in Tables 3-5 through 3-7. Although the radial dimensions of all loadings were the same, the total number of fuel rods differed when fuel rods were removed to create moderator gaps. The critical moderator height, before shimming with boric acid, has an absolute accuracy of ± 0.1 cm for Cores XVIII and XIX and ± 0.2 cm for Core XX. The lower accuracy for Core XX resulted from difficulties in keeping the boron concentration exactly constant, as is discussed below.

The statistical accuracy of the results is approximately $\pm 5\%$, which includes an uncertainty of 0.3 to 1.0 cents (depending on $\partial\rho/\partial h$) due to the critical moderator height and an uncertainty of 3 to 5% due to errors in $\partial\rho/\partial h$ and the integration. The reactivities can be converted to absolute units using the calculated values of β_{eff} listed for each core. The calculations take into account the delayed neutrons from U^{238} fissions and from (γ, n) processes on deuterium as well as the greater nonleakage probability for delayed neutrons. The accuracy of this calculation is difficult to estimate, but the reliability of reactivity measurements by this technique can be assessed by comparing the results with those derived by the alternate technique of boron addition.

The boron concentration required to make each loading critical at 145.0 cm is given in Tables 3-5 through 3-7. Some difficulty was experienced in keeping the moderator composition constant during these measurements. For Core XVIII, the reactivity increased at the rate of about (0.5 ± 0.1) cent per day, which is attributed to moderator degradation by exchange with H_2O vapor in the atmosphere. For Core XX, the reactivity decreased at a rate corresponding to an increase in boron concentration of (0.0005 ± 0.0003) gm B/l per run, which was shown to be due to water evaporation. Essentially no change was observed in Core XIX; presumably the two effects compensated. The results were corrected for these effects, since comparative runs were made over a several day period. Although the boron concentration for each loading was shimmed to make the critical height within 1 to 2 cm of 145 cm, an additional small correction was applied to normalize the results to exactly

145 cm. The data of Figure 3-7, with an uncertainty of 5 to 10%, were used for this purpose.

The boron concentrations listed in the tables are normalized to the measured concentration of Loading G, which has an absolute accuracy of about $\pm 0.5\%$. The boron concentrations for the other loadings are calculated from the weights of boric acid added to the mixture for Loading G to improve the relative accuracy of the results. The calculated concentrations, however, always agreed with the measured concentration to within the accuracy of the analyses ($\pm 0.5\%$). The uncertainties listed in the tables are, therefore, relative values based on the errors discussed above; on an absolute basis an additional 0.5% analytical error should be added.

Table 3-5. Reactivity Worth of Perturbers in Core XVIII

Loading designation and description	No. of fuel rods	Critical moderator height, cm*	Reactivity, cents**		Boron concentration for h = 145 cm, gm B/l	$\partial\rho/\partial N_B$ \$/gm B/l
			$\partial\rho/\partial h$	Boron		
A-Unperturbed lattice	5137	107.9	227	231	0.0856 ± 0.0005	27
B-Boral blade in lattice	5137	143.5	5.6	7.2	0.0020 ± 0.0002	36
C-Moderator gap	5120	101.9	287	273	0.1092 ± 0.0006	25
D-Aluminum blade in C	5120	103.2	272	260	0.1039 ± 0.0007	25
E-Cadmium blade in C	5120	128.2	79	79	0.0246 ± 0.0001	32
F-Boral blade in C	5120	144.6	1.5	3.5	0.00095 ± 0.00006	37
G-Boral cruciform rod	5116	145.0	(0.0)	(0.0)	(0.0000)	--
H-Aluminum cruciform rod	5116	102.2	283	271	0.1082 ± 0.0007	25

* 72.1 mole % D₂O, 0.0 gm B/l.** $\beta_{\text{eff}} = 0.00709$.

Table 3-6. Reactivity Worth of Perturbers in Core XIX

Loading designation and description	No. of fuel rods	Critical moderator height, cm*	Reactivity, cents**		Boron concentration for h = 145 cm, gm B/l	$\partial\rho/\partial N_B$ \$/gm B/l
			$\partial\rho/\partial h$	Boron		
A-Unperturbed lattice	5137	97.7	263	274	0.9443 ± 0.0047	16.5
B-Boral blade in lattice	5137	137.3	24	23	0.7923 ± 0.0040	16.7
C-Moderator gap	5120	96.6	272	276	0.9456 ± 0.0048	16.5
D-Aluminum blade in C	5120	--	--	--	--	--
E-Cadmium blade in C	5120	125.0	75	79	0.8254 ± 0.0041	16.7
F-Boral blade in C	5120	142.3	7.6	7.4	0.7827 ± 0.0040	16.8
G-Boral cruciform rod	5116	145.0	(0.0)	(0.0)	0.7783 ± 0.0041	--
H-Aluminum cruciform rod	5116	97.3	266	269	0.9413 ± 0.0048	16.5

* 50.0 mole % D₂O, 0.7783 gm B/l.

** $\beta_{\text{eff}} = 0.00698$.

Table 3-7. Reactivity Worth of Perturbers in Core XX

Loading designation and description	No. of fuel rods	Critical moderator height, cm*	Reactivity, cents**		Boron concentration for h = 145 cm, gm B/l	$\partial\rho/\partial N_B$ \$/gm B/l
			$\partial\rho/\partial h$	Boron		
A-Unperturbed lattice	5137	93.2	224	225	1.838 ± 0.005	13.6
B-Boral blade in lattice	5137	131.7	32	41	1.705 ± 0.005	13.8
C-Moderator gap	5120	102.3	162	156	1.790 ± 0.005	13.6
D-Aluminum blade in C	5120	100.6	172	--	--	--
E-Cadmium blade in C	5120	127.6	45	48	1.710 ± 0.008	13.7
F-Boral blade in C	5120	139.5	11	15	1.686 ± 0.003	13.8
G-Boral cruciform rod	5116	145.0	(0.0)	(0.0)	1.675 ± 0.004	--
H-Aluminum cruciform rod	5116	103.2	156	151	1.786 ± 0.003	13.6

* 0.0 mole % D₂O, 1.675 gm B/l.** $\beta_{\text{eff}} = 0.00688$.

3.4. Flux Distributions

3.4.1. Techniques

Flux distributions in the vicinity of the perturbers 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 calibrated for dysprosium content by irradiating them in a constant flux and counting their activities; 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 transverse to 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 could be accurately aligned relative to the perturber and adjacent fuel rods. Near the perturber, the foils were spaced on single-pitch intervals for bare runs and 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 beta counted for 1 minute on each side in each of three end-window gas-flow proportional counters. Count rates were at least 10,000 counts/min except for 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 loadings of Core XVIII, fine structure measurements were also made near the perturber on intervals of $1/4$ pitch (0.378 cm) 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.

The flux distribution in Core XVIII-G, which contained a Boral cruciform blade, was mapped over one octant in the midplane of the core (65 cm above the bottom of the active fuel). One flux traverse was made along the core radius; the others were parallel to this one but

displaced by rows of fuel rods (see Figure 3-20). The bare and cadmium-covered gold foil activations were made by using the same techniques described above.

3.4.2. Results

The results of the standard runs are shown in Figures 3-8 through 3-17. To simplify the presentation of the data, the flux traverses are symmetrized, i.e., north and south activities are average; no asymmetry in excess of the accuracy of the data was observed. The thermal flux was obtained from both the gold (solid circles) and dysprosium (open circles) data. Since bare dysprosium foils respond primarily to thermal neutrons, the thermal component of the activity could be obtained with a statistical accuracy of 1 to 2% by multiplying the bare activity by $(C_{Dy} - 1) / C_{Dy}$, where C_{Dy} is the measured cadmium ratio. This ratio was larger than 0.9 in all cores. The gold data were derived by subtracting the normalized cadmium-covered activity from the bare activity. Since the gold cadmium ratio was as small as 1.4, the accuracy of the thermal component was much poorer, of the order of 10 to 15%.

The second curve in each figure is the normalized saturated activity of the cadmium-covered gold foils, accurate to about $\pm 1\%$, and the third curve is the cadmium ratio of gold accurate to about $\pm 2\%$. The lower curve is the ratio of the thermal activity of dysprosium to the thermal activity of gold arbitrarily normalized to unity at distances far from the perturbation. The departure from unity near the perturber shows that the thermal flux shapes measured by the two materials differ. This difference is probably due to spectral effects since the cross section of dysprosium varies more rapidly than $1/v$ whereas that of gold in the thermal region decreases somewhat less slowly than $1/v$.

Figures 3-18 and 3-19 show the fine structure in Core XVIII near the perturbers. Figure 3-20 shows a series of flux traverses near the cruciform perturber in Core XVIII. The results are converted to a contour diagram of the midplane thermal flux distribution in Figure 3-21.

3.5. Buckling and Reflector Savings

3.5.1. Techniques

The critical buckling of the unperturbed lattice Core XVIII-A was derived from two radial and two axial flux traverses using bare and cadmium-covered 0.259-inch diameter by 0.005-inch-thick gold foils. The foils were mounted on 0.005-inch-thick by 0.5-inch-wide steel tapes and were spaced 5 cm axially and 1.511 cm radially (double pitch 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 two fuel rods west of the core axis.

After 20-minute activations at power levels between 200 and 400 watts with all control blades withdrawn, the foils 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. Bucklings were derived from least square fits of 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 as the range of the fit was reduced.

Similar procedures were followed in the unperturbed loadings of Cores XIX and XX, except that the foils for the axial traverses were mounted on a fuel rod. To provide clearance for the foils and covers, the diameter of the fuel rod was reduced by machining the aluminum cladding at 5 cm intervals. The foils on the special fuel rod were located 7.5 pitches north and 2.5 pitches west of the core axis.

Axial bucklings were also measured in many of the perturbed cores to obtain the relationship between axial reflector savings and critical moderator height. The bucklings were derived from bare gold flux traverses using the criterion of constant buckling as the range of the fit changed to define the asymptotic region. In the perturbed lattices of Core XVIII, the foils were mounted on steel tapes located 9 pitches east and 3.5 pitches south of the core axis; in Cores XIX and XX they

were mounted on the special fuel rod and were located 7.5 pitches north and 2.5 pitches west of the core axis. Two measurements were made in Core XVIII-G using the special fuel rod, one along the core axis and one 15 pitches north of the core axis.

3.5.2. Results

The bucklings of the unperturbed lattices are listed in Table 3-8, where a small correction to the measured axial buckling

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

has been applied to reduce the data to the measured unperturbed critical moderator height. The reflector savings were derived from the bucklings, critical moderator heights, and core radii, which were constant at 61.11 cm.

Table 3-8. Critical Buckling of Unperturbed Cores (Loading A)

<u>Parameter</u>	<u>Core XVIII</u>	<u>Core XIX</u>	<u>Core XX</u>
D ₂ O concentration, mole %	72.1	50.0	0.00
Boron concentration, gm B/l	0.00	0.778	1.675
Moderator height, cm	107.9	97.7	93.2
Radial buckling, $\times 10^{-4} \text{ cm}^{-2}$	8.76 ± 0.06	11.79 ± 0.14	12.4 ± 0.3
Axial buckling, $\times 10^{-4} \text{ cm}^{-2}$	5.99 ± 0.05	7.12 ± 0.03	7.82 ± 0.04
Total buckling, $\times 10^{-4} \text{ cm}^{-2}$	14.75 ± 0.08	18.91 ± 0.14	20.2 ± 0.4
Radial reflector savings, cm	20.1 ± 0.3	8.9 ± 0.4	7.2 ± 0.7
Axial reflector savings, cm	20.4 ± 0.6	20.1 ± 0.3	19.1 ± 0.04

The axial bucklings and reflector savings are summarized in Table 3-9 and plotted in Figure 3-22. As predicted by the $\partial\rho/\partial h$ data, the axial reflector savings remain constant for moderator heights below about 130 cm. The axial reflector savings for the loading with the Boral cruciform rod (Loading G) appears to be 1 cm less when measured along the core axis. 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 3-9. Axial Buckling and Reflector Savings

<u>Loading designation</u>	<u>Moderator height, cm</u>	<u>Axial buckling, 10^{-2} cm^{-1}</u>	<u>Axial reflector savings, cm</u>
<u>Core XVIII - 72.1 mole % D_2O, 0.0 gm B/l</u>			
A	107.9	2.448 ± 0.010	20.4 ± 0.6
B	143.5	1.961 ± 0.006	16.7 ± 0.5
C	101.9	2.570 ± 0.012	20.3 ± 0.6
E	128.2	2.113 ± 0.010	20.5 ± 0.7
F	144.6	1.938 ± 0.004	17.5 ± 0.4
G	145.0	1.946 ± 0.007	16.6 ± 0.6
G*	145.0	1.956 ± 0.007	15.5 ± 0.6
<u>Core XIX - 50.0 mole % D_2O, 0.778 gm B/l</u>			
A	97.7	2.668 ± 0.006	20.1 ± 0.3
B	137.3	2.023 ± 0.005	18.0 ± 0.4
C	96.6	2.707 ± 0.007	19.5 ± 0.3
F	142.3	1.990 ± 0.004	15.6 ± 0.3
<u>Core XX - 0.0 mole % D_2O, 1.675 gm B/l</u>			
A	93.2	2.797 ± 0.005	19.1 ± 0.4
B	131.7	2.087 ± 0.005	18.8 ± 0.4
C	102.3	2.588 ± 0.008	19.1 ± 0.4
F	139.5	2.011 ± 0.005	16.7 ± 0.4

* Measured along core axis.

Figure 3-1. Core XVIII - Vertical Section

Figure 3-2. Core XVIII - Horizontal Section

Figure 3-3 View of Core XVIII-G

5-foot Diameter
Core Tank

Safety Blade

Cruciform Perturber
(Loading G)

Figure 3-4. Locations of Perturbers

B - Boron Blade in Uniform Lattice

C - Moderator Gap in Center of Lattice

D - Aluminum Blade in Gap

E - Cadmium Blade in Gap

F - Boron Blade in Gap

G - Boron Cruciform Perturber in Gap

H - Aluminum Cruciform Perturber in Gap

Figure 3-5. $\partial\rho/\partial h$ Vs h for Core XVIII

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

Figure 3-7. Reactivity Worth of Boron

Figure 3-8. Flux Distribution in Core XVIII-B

Figure 3-9. Flux Distribution in Core XVIII-C

Figure 3-10. Flux Distribution in Core XVIII-E

Figure 3-11. Flux Distribution in Core XVIII-F

Figure 3-12. Flux Distribution in Core XIX-B

Figure 3-13. Flux Distribution in Core XIX-C

Figure 3-14. Flux Distribution in Core XIX-F

Figure 3-15. Flux Distribution in Core XX-B

Figure 3-16. Flux Distribution in Core XX-C

Figure 3-17. Flux Distribution in Core XX-F

Figure 3-18. Fine Structure in Core XVIII-C

Figure 3-19. Fine Structure in Core XVIII-F

Figure 3-20. Flux Distribution in Core XVIII-G

Figure 3-21. Midplane Flux Distribution in Core XVIII-G

Figure 3-22. Axial Reflector Savings

4. PARTIALLY INSERTED ROD EFFECTS

4.1. Description of Core

The effects on reactivity and flux distribution of a partially inserted Boral cruciform control rod were measured in two loadings of Core XVIII. The unperturbed core, described in Section 3, consisted of 2.46%-enriched UO_2 fuel rods arrayed in a cylindrical lattice having a M/W ratio of 1.001, a moderator composition of 72.1 mole % D_2O , and an effective radius of 61.11 cm. In Loading G of Core XVIII, a Boral cruciform rod was fully inserted in the center of the uniform lattice, and in Loading H the Boral rod was replaced by a similar size, fully inserted aluminum cruciform follower. The results of these experiments have been reported in Section 3.

The experiments described here were similar to Loadings G and H except that axial asymmetry was introduced by partially inserting the cruciform rod. The Boral cruciform rod was approximately 1/3 withdrawn from the core in Loading GA and approximately 2/3 withdrawn in Loading GB. These withdrawals were accomplished by fastening aluminum cruciform followers of proper lengths to the bottom of the Boral cruciform rod and allowing the Boral cruciform rod to project equivalent distances above the core. The Boral and aluminum sections were identical in dimensions and composition to Loadings G and H described in Tables 3-3 and 3-4. The composite cruciform rods rested on the top of the bottom grid plate, and the aluminum sections were 49.0 cm long (51.2 cm relative to the bottom of active fuel) in Loading GA and 98.0 cm long (100.2 cm relative to the bottom of active fuel) in Loading GB.

4.2. Reactivity Measurements

The reactivity worth of the partially inserted cruciform rod was measured by using the boron addition technique described in Section 3.

The alternate technique of deriving reactivity from the critical moderator height and $\partial\rho/\partial h$ data was not used because these loadings were not axially symmetrical. The results are listed in Table 4-1, where the boron concentration is that required to raise the moderator level to the reference 145.0 cm level. The results for the fully inserted Boral and aluminum cruciforms given in Section 3 are also listed for comparison.

Table 4-1. Reactivity Worth of Cruciform Perturbers in Core XVIII

Loading designation and description	Number of fuel rods	Boron reactivity, ρ	Boron concentration for $h = 145.0$ cm, gm B/l
G-Boral cruciform rod	5116	(0.0)	(0.0000)
GA-Rod 1/3 withdrawn	5116	80	0.0251 ± 0.0001
GB-Rod 2/3 withdrawn	5116	236	0.0874 ± 0.0005
H-Aluminum cruciform rod	5116	271	0.1082 ± 0.0007

4.3. Flux Distributions

Axial flux distributions were mapped in the octant between north and northwest using bare and cadmium-covered Dy-Al foils. The foils were 0.259 inch in diameter by 0.007 inch thick and contained approximately 5 wt% dysprosium. Calibration factors were obtained by irradiating sets of foils in a constant flux and counting their activities. The foils were mounted on the surface of a fuel rod that was used as a foil holder and inserted in the lattice in the positions shown in Figure 4-1. To provide clearance for the foils and covers, the diameter of the fuel rod was reduced to 0.455 inch by machining the aluminum cladding at 5 cm intervals. As shown in the figure, the foils were mounted along the southeast side of the fuel rod in Loading GA and along the east side in Loading GB.

The foils were activated for 20 minutes at power levels between 200 and 400 watts, with all control blades fully withdrawn, and beta counted for 1 minute on each side in each of three end-window gas-flow proportional counters. Count rates were at least 10,000 counts/min

except for cadmium-covered traverses, where they were occasionally as low as 1000 counts/min. Bare and cadmium-covered runs were normalized by four gold monitor foils located against the outside surface of the core tank.

The bare foil saturated activities were corrected for variations in epicadmium activation by multiplying them by $(C_{Dy}-1)/C_{Dy}$, where C_{Dy} is the cadmium ratio of the Dy-Al foils. This factor was essentially constant at 0.91 to 0.92 over most of the core. In the most extreme case (Traverse a) it varied between 0.95 at the aluminum end and 0.88 at the Boral end; for Traverse e, the variation was only 0.94 to 0.91. Since the correction factor was close to unity and varied substantially only in the vicinity of the perturber, relatively few cadmium-covered runs were needed.

The thermal flux distributions are shown in Figures 4-2 through 4-7, where all the data are normalized to unit reactor power. The axial distance is measured relative to the bottom of the active fuel in the fuel rods. The statistical accuracy of the results is approximately $\pm 2\%$, but the discrepancy between the thermal flux as measured by gold and by dysprosium noted in Section 3 may introduce an additional small systematic error in the traverses near the perturber. The axial flux perturbation appears to damp out much more quickly than in light-water moderated cores, due to the larger migration area, and the flux shapes approach the cosine distribution fairly closely at a distance of five lattice spacings from the perturber.

Figure 4-1. Locations of Axial Flux Traverses

Figure 4-2. Axial Flux Distributions in Core XVIII-GA

Figure 4-3. Axial Flux Distributions in Core XVIII-GA (Cont'd)

Figure 4-4. Axial Flux Distributions in Core XVIII-GA (Cont'd)

Figure 4-5. Axial Flux Distributions in Core XVIII-GB

Figure 4-6. Axial Flux Distributions in Core XVIII-GB (Cont'd)

Figure 4-7. Axial Flux Distributions in Core XVIII-GB (Cont'd)

5. PERTURBATION CALCULATIONS

5.1. Introduction

Calculations have been made in an attempt to match experimental thermal flux shapes, reactivities, and boron worths in a number of perturbed cores. Three D₂O concentrations were considered, which corresponded to Core XVIII with 72% D₂O, Core XIX with 50% D₂O, and Core XX with 0% D₂O. Several perturbations in each of these cores were investigated. Diagrams of the experimental perturbations are given in Figure 3-4. All cores had 2.46%-enriched fuel and a M/W ratio of 1.001.

5.2. Calculation Methods

All calculations were made with PDQ-4, a code for the Philco 2000 computer, which solves the few-group neutron diffusion equations in two dimensions. The diffusion equations were of the form:

$$-D\nabla^2 \phi_i + \left(\Sigma_i^a + \Sigma_i^R \right) \phi_i = \frac{X_i S}{\lambda} + \Sigma_{i-1}^R \phi_{i-1}, \quad i = 1, \dots, 4$$

where

$$\Sigma_0^R = \Sigma_k^R = 0$$

$$S_i = \sum_{i=1}^k (\nu \Sigma^f)_i \phi_i$$

D = diffusion coefficient

Σ^a = absorption cross section

Σ^R = removal cross section

X_i = fraction of the total fission spectrum in group i

ν_i = average number of neutrons provided per fission in group i

Σ^f = fission cross section

S = fission source

ϕ = neutron flux

λ = critical eigenvalue

A detailed description of this code is given in Reference 21.

The input to the PDQ-4 code consisted of a description of the mesh line spacing, the location of each composition, i. e. , control rod meat and cladding, core, reflector, etc. , and the four-group coefficients of each composition.

The reactor core cross section was represented by a mesh made up of a series of intersecting lines. All composition boundaries fell on mesh lines. Thus, control rod meat, cladding, and moderator gaps were shown as discrete regions. The fuel region was homogenized.

The output consisted of a complete edit of the input, a picture of the mesh showing composition location, composition areas, integrated and averaged fluxes for each composition, and the point fluxes and source.

5.3. Input Preparation

All inputs for the PDQ-4 calculations were prepared with the BPG computer code⁷. Four-group coefficients were calculated for each of the compositions. The group coefficient inputs for the PDQ-4 calculations were obtained as condensed group coefficients from the BPG code.

The energy groups used were as follows:

<u>Group</u>	<u>Energy range</u>
1	10 mev - 0.714 mev
2	0.714 mev - 3739 ev
3	3739 ev - 0.4 ev
4	Thermal - 0.4 ev

Experimental disadvantage factors were used. The RIP code, which is described in detail in BAW-1273⁷, was used to calculate the resonance distribution function (ψ set) necessary for the BPG-II calculations. These ψ sets were normalized to the U^{238} resonance integral for each case. The Hellstrand recipe with the Bell approximation self-shielding factors was used to generate the resonance integrals. The ψ set distributes the U^{238} absorption over the epithermal groups.

Two sets of calculations were made for each core loading. The k_{eff} of each loading was calculated for a critical moderator height of 145 cm. Since most of the loadings were actually critical at lower moderator heights, the calculated k_{eff} of each loading was normally greater

than 1.00. Next, the k_{eff} of each loading was calculated using a boric acid concentration experimentally determined to make the loading critical at 145 cm (See Tables 3-5 through 3-7). The difference in the two values was the calculated reactivity worth of the perturbation.

5.4. Comparison of PDQ-4 and Experimental Results

For comparison purposes, the experimental and calculated values of reactivity worth of the perturbation are shown in Table 5-1.

Table 5-1. Reactivity Worth of Perturbers

Core loading and description	Experimental reactivity		Calculated reactivity
	$\partial\rho/\partial h$	Boron	
18-A Unperturbed lattice	0.0161	0.0164	0.018
18-B Boral blade in lattice	.0004	.0005	--
18-C Moderator gap	.0203	.0194	0.022
18-D Aluminum blade in C	.0193	.0184	0.019
18-E Cadmium blade in C	.0056	.0056	0.005
18-F Boral blade in C	.0001	.0002	--
18-G Boral cruciform rod	0.0000	0.0000	0.000
19-A Unperturbed lattice	0.0184	0.0191	0.018
19-B Boral blade in lattice	.0017	.0016	0.002
19-C Moderator gap	.0190	.0193	0.019
19-F Boral blade in C	.0005	.0005	--
19-G Boral cruciform rod	0.0000	0.0000	0.000
20-A Unperturbed lattice	0.0154	0.0155	0.017
20-B Boral blade in lattice	.0022	.0028	0.002
20-C Moderator gap	.0111	.0107	0.012
20-F Boral blade in C	.0008	.0010	--
20-G Boral cruciform rod	0.0000	0.0000	0.000

The experimental data are identical to that of Tables 3-5, 3-6, and 3-7 except that calculated values of β_{eff} were used to convert the experimental data to absolute units. Because of the large core diameters, β_{eff} changed relatively little within the range of moderator heights

considered. Experimental values of reactivity determined by boron addition are also included. Differences between calculated and experimental values are less than 0.002. Since the solution of the PDQ-4 code is an iterative process, calculations of small reactivity changes (<0.001) are of dubious value. Thus, all calculated values are given to only three decimal places, and loadings with small boron changes were not calculated.

5.5. Comparison of Thermal Flux Distributions

In addition to reactivity worths, the PDQ-4 code calculated thermal flux shapes for each of the perturbations. These calculated flux shapes were normalized to the corresponding experimental flux shapes by equating the average thermal fluxes. An absolute comparison was not possible since the experimental thermal flux averaged over all the core was not available. Except for Loading G, the thermal flux distribution was calculated along the core radius transverse to the perturber and corresponds to the experimental transverse in a plane 65 cm above the bottom of the fuel. The location of the measured and calculated flux distributions of Loading G is shown in Figure 5-5.

The experimental and calculated flux traverses are plotted in Figures 5-1 through 5-11. Comparisons are given for Core XVIII Loadings B, C, E, F, and G; Core XIX Loadings B, C, and F; and Core XX Loadings B, C, and F.

Experimental and calculated flux shapes generally agree. Agreement is probably best for the C Loadings (moderator gap) and poorest for the E Loading (cadmium blade). Normally the calculated fluxes exhibit a greater slope at the surface of the perturbation and higher values a few centimeters away from the perturber than the experimental fluxes. Agreement seems to improve with decreasing D_2O concentration. The poor agreement for the cadmium blade (Loading E) is due in part to the poisoned rod boundary condition, which specifies that the thermal flux is zero at the effective extrapolation distance. Diffusion theory was used to describe the thermal flux inside the Boral blades; thus the thermal flux inside the blade was finite. Both treatments (poison rod boundary condition and diffusion theory) give about the same calculated reactivity worth. From a design standpoint the small difference in flux shape is of little importance as long as the calculated reactivity worth is correct.

Figure 5-1. Thermal Flux Distribution in Core XVIII- B

Figure 5-2. Thermal Flux Distribution in Core XVIII-C

Figure 5-3. Thermal Flux Distribution in Core XVIII-E

Figure 5-4. Thermal Flux Distribution in Core XVIII-F

Figure 5-5. Thermal Flux Distribution in Core XVIII-G

Figure 5-6. Thermal Flux Distribution in Core XIX-B

Figure 5-7. Thermal Flux Distribution in Core XIX-C

Figure 5-8. Thermal Flux Distribution in Core XIX-F

Figure 5-9. Thermal Flux Distribution in Core XX-B

Figure 5-10. Thermal Flux Distribution in Core XX-C

Figure 5-11. Thermal Flux Distribution in Core XX-F

6. PARTIALLY INSERTED ROD CALCULATIONS

6.1. Introduction and Core Description

The partially inserted rod experiments were variations of Core XVIII Loading G, which was critical at a moderator height of 145 cm with a 6-inch cruciform Boral rod fully inserted in a moderator gap along the core axis. The moderator was 72.1 mole % D_2O and unborated. In Loadings GA and GB the rod was approximately $1/3$ and $2/3$ withdrawn, and criticality was maintained at a moderator height of 145 cm by the addition of 0.0251 and 0.0874 gm B/l of moderator for Loadings GA and GB, respectively. A more detailed description of the loadings with partially inserted rods is given in Section 4.1.

6.2. Calculation Methods

TKO, a three-dimensional neutron diffusion code for the IBM-704 computer,²² was used for the partial rod insertion calculation. TKO is a few group, steady state, computer code, which solves the neutron diffusion equation in three dimensions (x, y, z). The equations have the same form as those described in Section 5.2.

In TKO the reactor core was represented by a rectangular parallelepiped that was symmetric with respect to the x-y plane. Eighth core symmetry was assumed. The parallelepiped was in turn subdivided into smaller rectangular parallelepipeds by a mesh of horizontal and vertical planes. The mesh was constructed in such a way that all region interfaces occurred on mesh planes. Either zero flux or zero current boundary conditions were applied at each of the external boundary planes.

The input for the three-dimensional TKO was similar to that for the two-dimensional PDQ-4 described in Section 5.3. The spacing between adjoining x-y planes was the only additional information required. Because of limitations in mesh size, the control rod meat and clad were homogenized.

Output consisted of a complete edit of the input, a picture of each x-y plane in which a composition change occurred, the composition volumes, the integrated and averaged fluxes and source for each composition, and the point fluxes and source.

As a check, TNT-1, a revised and expanded version of TKO written for the Philco 2000 computer,²³ was used to calculate Loading GA, the 1/3 withdrawn case. The chief difference between the two codes lies in the number of available mesh points. TNT-1 handles approximately four times more mesh points than TKO. Thus, greater detail in core description was possible. Most of the additional mesh points were used in the x-y planes. The number of planes was increased about 30%.

6.3. Comparison of TKO Results with Experimental Results

Positions a, e, and n (see Figure 4-1) were chosen for comparison with calculated results. As with the flux traverses described in Section 5.5, the calculated flux was normalized to the experimental flux by equating the average thermal flux for the particular traverse. Therefore, flux shape is the only valid comparison of experimental and calculated data. Comparisons were made for both the 1/3 and 2/3 withdrawn rod (Loadings GA and GB, respectively). The results are plotted in Figures 6-1 through 6-6.

In general, the flux shapes calculated with TKO agreed very well with the experimental traverses. The agreement was especially good with the rod 2/3 withdrawn. Agreement between theoretical and experimental data is poorest in the immediate vicinity of the rod, but from a design standpoint this is, however, not so important since there is minimum heat produced in this region. Loading GA, the 1/3 withdrawn case (Figures 6-1 through 6-3), shows the greatest discrepancy between experiment and theory. The calculated flux shape, though very similar to the experimental shape, does not show the extreme variation. This is especially true of the traverse nearest the control rod, Figure 6-1. One factor that may affect the calculated flux shape lies in the choice of control rod treatment. As described earlier the control rod can be treated as a black thermal absorber in which the thermal flux is made to go to zero, or the rod can be treated as a diffusion region with actual boron thermal cross section. The black thermal absorber treatment

was used here, which resulted in less flux depression by the rod. The apparent effect is to raise the flux level along the rod without particularly affecting the flux peak below the bottom of the rod. As a result the spread between the maximum and minimum is less with this treatment. The location of the calculated flux peak agrees with the experimental peak within several centimeters. Flux shapes using Code TNT were essentially identical with those using Code TKO.

6.4. Calculated k_{eff}

Calculations of the clean critical and perturbation experiments described earlier use measured bucklings. The TKO calculations are in three dimensions, which removes the buckling dependence. The k_{eff} generated by TKO agrees well with one and two dimensional calculations. The calculated values of k_{eff} were 1.019, 1.016, and 1.012 for the fully inserted, 1/3 withdrawn, and 2/3 withdrawn rods, respectively.

Figure 6-1. Axial Thermal Flux in Core XVIII-GA, Traverse a

Figure 6-2. Axial Thermal Flux in Core XVIII-GA, Traverse e

Figure 6-3. Axial Thermal Flux in Core XVIII-GA, Traverse n

Figure 6-4. Axial Thermal Flux in Core XVIII-GB, Traverse a

Figure 6-5. Axial Thermal Flux in Core XVIII-GB, Traverse e

Figure 6-6. Axial Thermal Flux in Core XVIII-GB, Traverse n

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