October 1975

PHYSICS VERIFICATION PROGRAM,
PART III, TASKS 8-11
— SUMMARY REPORT —

by

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ERDA Contract No. AT(11-1)-3109
B&W Contract No. 41-2007
(WO-6258-01, 6457-01, RDE 2561-01 & 2072-02)

Prepared for
THE U.S. ENERGY RESEARCH & DEVELOPMENT ADMINISTRATION
by
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ACKNOWLEDGMENT

The authors wish to thank W. T. Hamilton and J. O. Towles for their assistance on this project.

Babcock & Wilcox
Research and Development Division
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Report BAW-3647-33

October 1975

Physics Verification Program, Part III,
Tasks 8-11 - Summary Report

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Key Words: Prompt Responding, Incore Neutron Flux Detectors, Power Density Profiles, Pressurized Water Reactor, Critical Assembly, Perturbed Lattices, Neutron Absorption, Reactivity Worth, Lumped Burnable Poison, Flux Profiles, Fuel Rod Gaps, Fuel Densification, Fission Rate

ABSTRACT

In experimental Task 8, the detectability of gaps between fuel pellets in fuel rods was determined by measuring thermal flux perturbations in the fuel assembly instrument guide tube. The power peaking in fuel rods surrounding a gapped fuel rod and the power and flux depression due to an Inconel grid were also determined. The experimental assembly - a water-moderated, slightly enriched UO_2 lattice perturbed with a fuel rod containing a void - was arranged to mock up the fuel elements of a commercial pressurized water reactor. The neutron flux near the perturbation was measured with gold foils and with a special rhodium incore detector having a 1-inch emitter. The results can serve as a check of analytical calculations on the effects of a fuel gap and its detectability.

Experimental Task 9 was conducted to compare the fission rate within the fuel rods of a critical assembly with the neutron absorption rate in adjacent pins containing simulated lumped burnable poison (LBP) material. The experimental assembly, a water-moderated, slightly enriched UO_2 lattice perturbed by the simulated LBP and dissolved boric acid, was arranged to mock up the fuel elements of a commercial pressurized water reactor (PWR). The results can serve to check analytical techniques used in the design of large PWRs.

Experimental Task 10 was conducted to obtain data to use in assessing the relative magnitude of the neutron- and gamma-induced signal components from an all-solid, prompt-responding incore detector. The measurements were taken in three separate, slightly enriched UO_2 lattices, which are designed to provide a wide range for the neutron-to-gamma ratio and for the neutron spectrum.

In experimental Task 11, the reactivity and power perturbation effects of poison pins in mockups of 17 by 17 fuel assemblies and the depression of power density in gadolinium-laden fuel pellets were measured. The experimental facility - a water-moderated, slightly enriched UO_2 lattice - was arranged to mock up the fuel assemblies of a commercial pressurized water reactor. Each assembly contains 24 poison pin positions.

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1. INTRODUCTION

In October 1972, Babcock & Wilcox (B&W) initiated Part III, Task 8, of the Physics Verification Program. Tasks 9, 10, and 11 were initiated in April 1973, October 1973, and January 1974, respectively. The program has been jointly sponsored by B&W and the U. S. Atomic Energy Commission (now the Energy Research & Development Administration). The experimental task objectives are as follows:

Task 8

1. To determine the detectability of gaps between fuel pellets by measuring thermal neutron flux perturbations in the fuel assembly instrument guide tube.
2. To determine power peaking in the surrounding fuel pins.
3. To determine the flux depression due to an Inconel grid.

Task 9

To measure the fission rate in UO_2 fuel at selected positions within a critical assembly and compare it with the neutron absorption rate in the boron of a simulated lumped burnable poison.

Task 10

To obtain experimental data for use in assessing the relative magnitude of the neutron and gamma induced signal components from an all-solid, prompt-responding incore detector.

Task 11

To obtain experimental data for use in assessing the reactivity and power perturbation effects of poison pins in 17 by 17 fuel assembly mockups, and measure the depression of power density in gadolinium-laden fuel pellets.

This report summarizes all of the experimental results obtained under these tasks. In several instances, data previously reported in quarterly technical reports have been reanalyzed, so that the results given here may differ slightly from those reported earlier.¹⁻⁸ References 9 through 14 summarize other completed tasks.

2. TASK 8 - FUEL GAP DETECTABILITY STUDY (V. D. McAdams, M. N. Baldwin)

2.1. Description of Assembly

2.1.1. Facility

The facility, located at B&W's Lynchburg Research Center, is a critical assembly within a 5-foot-diameter by 6.5-foot-high core tank with 0.5-inch-thick aluminum walls. The water handling equipment, instrumentation, control system, and other auxiliaries are conventional.

2.1.2. Standard Fuel Rods

Table 2-1 summarizes the physical properties of the standard fuel rods. The uncertainties are standard deviations of the means obtained from vendors' quality control data and check measurements on from 50 to 100 randomly selected samples. The impurities are given as the summation of $N_i \sigma_i$, where N_i is the concentration of each impurity per cubic centimeter of the oxide fuel, and σ_i is the corresponding microscopic absorption cross section at 2200 m/s. The end caps are aluminum plugs 0.125 inch thick. A 1-inch-long dead space between the top of the fuel pellet stack and the top end cap is filled with Kaowool.

2.1.3. Gapped Fuel Rods

Six fuel rods were fabricated with voids or gaps. The cladding was not collapsed around the gaps on any of these rods. Four of the rods had a 3.01 ± 0.005 inch gap, the fifth rod had a 1.51 ± 0.003 inch gap, and the sixth rod had a 0.76 ± 0.003 inch gap. The midplane of the gap in each of the rods was 30.03 ± 0.05 inches above the base plate. A 0.405-inch-diameter aluminum spacer plug was inserted in the bottom of the rods (if needed) to maintain the height of the gap. Thus, the gaps were centered at a core height identical to that of the center of one of the fixed rhodium emitters in the composite incore detector assembly (section 2.1.4).

The fuel gap was maintained by a 0.405-inch-OD by 0.016-inch-wall aluminum tube. The ends of the tube were covered with 0.405-inch-diameter by 0.005-inch-thick aluminum discs to prevent chips from the pellets from entering the void. Figure 2-1 shows a typical fuel rod with a 3-inch gap and the aluminum spacer tube used to create the gap.

As illustrated in Figure 2-2, a fuel rod with the cladding collapsed at the location of the void was simulated by using a split fuel rod with a free-flooding aluminum sleeve joining the two sections of the fuel rod. The sleeve, a 4-inch-long by 0.475-inch-OD by 0.411-inch-ID aluminum tube, was reamed out to 0.443-inch ID for the first 0.5-inch on each end in order to mate with the end on the split fuel rod. The center section of the sleeve was drilled with many small holes to allow free flooding of the sleeve. The length of the free flooding section is 2.986 inches. The end plugs on the split fuel rod are 0.125-inch thick, giving a total void of 3.236 inches in the fuel for the collapsed clad rod. The center of the void for this rod is 30.79 inches above the base plate.

2.1.4. Composite Incore Assembly

A composite incore detector assembly, similar to that used in pressurized water reactors, is positioned in the center of the critical assembly during all measurements. The composite assembly (Figure 2-3) contains seven rhodium detectors, which are equally spaced along the vertical axis of the core. To aid in positioning the assemblies and to provide additional strength, type 304 stainless steel filler rods (0.0625-inch OD) are placed between the end caps of the assemblies and the end of the rhodium detectors.

The composite assembly comprises a 0.0316-inch-OD by 0.031-inch-wall outer sheath, a 0.125-inch-OD by 0.093-inch-ID calibration tube, a 0.062-inch-OD thermocouple, a 0.062-inch-OD background detector, and seven rhodium detectors. The thermocouple and detectors are swaged between the calibration tube and the outer Inconel sheath.

2.1.5. Core Description

Top and bottom plates align the fuel rods in the core tank. The top and bottom egg-crate grid plates are 1-inch wide, slotted aluminum strips, which are interlocked to form a square matrix. The 0.160-inch-thick strips are spaced on centers of 0.644 ± 0.002 inch.

The fuel rods are supported on a 2-inch-thick aluminum base plate, which is raised about 1 inch above the bottom of the 5-foot-diameter tank. The intervening space is filled with moderator. Moderator levels are measured from a reference plane at the bottom of the active fuel. Figure 2-4 shows the vertical dimensions of the core. The fuel rods and perturbing pins are uniformly spaced at intervals of the lattice pitch and are loaded to approximately a cylindrical geometry.

The safety blades are 8-inch-wide boral. Each blade is thin enough to pass between rows of fuel rods, so that uniform lattice spacing can be maintained. During measurements, the safety blades are held in a cocked position to minimize their contribution to core perturbations. Criticality is achieved by raising the level of the moderator. Boric acid in the moderator controls excess reactivity.

As shown in Figure 2-5, a loading diagram of the core, imaginary lines divide the core into nine 15 by 15 arrays or "elements." At the center position of each of the outer "elements" is a 0.25-inch-OD by 0.035-inch-wall Inconel 600 tube, which is sealed at the bottom to exclude water. Type 304 stainless steel sleeves (0.475-inch OD) at the bottom and near the top of the tubes center the tubes in the grids. The composite incore detector assembly occupies the center position of the central 15 by 15 array.

2.1.6. Moderator Boron

Excess reactivity was controlled by dissolving boric acid (H_3BO_3) in the demineralized water moderator. The boron concentration in parts per million (ppm) is defined as the grams of natural boron per 10^6 cc of moderator at 25C. The boron concentration was determined by titration against a standard KOH solution. The measurements have an absolute standard deviation of ± 3 ppm.

The measured moderator concentration was 1312 ppm. This concentration produces a k_{eff} of 1.0000 when the height of the moderator is 142.0 cm and all safety blades are fully withdrawn.

2.1.7. Auxiliary Reactivity Control

Within reasonable limits, excess reactivity was controlled by adjusting the boron concentration; however, minute changes in moderator concentration occurred continuously owing to evaporation of the moderator. Since these changes could

not be perfectly compensated for by water additions, a small degree of auxiliary control was required.

To provide this control, two fuel rods in the southwest quadrant were replaced with two Ag-In-Cd pins connected to a drive system. The total reactivity worth of these pins from the full-in to the full-out position was about 3 cents. Prior measurements have shown that the power profile for the area in which the data were taken is not affected by these poison pins.

2.2. Measurements

2.2.1. General

Four types of measurements were taken to accomplish the objectives of this task. Flux in the vicinity of the perturbation was measured with a rhodium incore detector, gold wire, and gold foil, and the power profile in the vicinity of the perturbation was measured.

Figure 2-6, a diagram of the central 15 by 15 array of the reactor core, shows the location of the composite assembly and water-filled positions. All other locations are filled with fuel rods. For convenience, some of the fuel rod positions have been assigned numbers and are referred to accordingly.

A gold flux wire measurement and a power profile measurement of pins 13, 14, and 15 were taken with an Inconel grid around the 16-pin insert. The 4 by 4 pin pitch grid was constructed from an Inconel sheet 0.020 inch thick by 1.5 inch wide. The grid was assembled on the 16-pin insert, and its midpoint was 30 inches above the base plate. The total mass of Inconel in the grid was 101.6 grams.

2.2.2. Special Rhodium Incore Detector and Drive System

A special rhodium incore detector (Figure 2-7) was fabricated for this program.* Table 2-2 lists the characteristics of the detector. The 1-inch emitter length was chosen to provide the resolution required to detect the small vertical perturbation produced by a gap of 0.75 to 3 inches and still generate currents large enough to be easily measurable. The detector operates on the principle of beta emission following neutron capture. The resultant electric current at equilibrium emission is proportional to the incident neutron flux.

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*The special rhodium detector was fabricated at B&W's Lynchburg Research Center by E. L. Glass and J. B. Wood under the direction of Dr. H. D. Warren.

The device shown in Figure 2-8 was used to position the detector in the core remotely. A small d-c motor drives a steel shaft through a set of gears. A helical groove is cut into the shaft so that a cable can be wound on it. The other end of the cable is attached to a negator motor, which takes up slack in the cable and keeps a constant tension on it. The detector was clamped to the cable so that it was pulled in and out of the core as the cable was wound and unwound from the shaft. A 10-turn, 1000-ohm potentiometer attached to the shaft provided position indication. The resistance was measured in the control room with a resistance bridge that was accurate to four places. A calibration curve of detector position versus resistance was obtained by recording the detector position and resistance reading every inch along the travel of the detector. By always moving the detector in the same direction and by taking detector flux measurements at the same points used to obtain the calibration curve, the reproducibility of detector measurements was maintained within ± 0.01 inch and the position accuracy was within ± 0.05 inch.

2.2.3. Measurements with Special Rhodium Incore Detector

The rhodium detector signal and background currents were measured with a Cary Model-401 vibrating reed electrometer (Figure 2-9). A Hewlett-Packard Model-3460B digital voltmeter and a Leeds and Northrup Speedomax H, 8-inch recorder were used as readout devices to gain precision in the measurements. A 50 foot, mineral-insulated cable connected the detector as positioned in the critical assembly to the electrometer preamplifier in the control room. The mineral-insulated cable, identical in construction to the lead section of the rhodium detector, was insensitive to both electromagnetic noise and temperature fluctuations. The electrical resistance from lead to sheath of the detector-cable combination was $>10^{13}$ ohms, and the capacitance of the combination was about 5.8 nf.

The high-resistance leak method was used to measure current; this is basically the measurement of the voltage drop across a precision resistor. The current output of the detector is determined by

$$I = E_r / R_1$$

where

E_r = voltage across R_1 ,

R_1 = resistance of the particular precision resistor in use within the Cary electrometer.

The Cary electrometer has three precision resistors with "nominal" values of 10^8 , 10^{10} , and 10^{12} ohms. For the present measurements, the nominal 10^{12} ohm resistor was used exclusively. Since the electrometer's amplifier gain is approximately 1000, the effective input resistance to the electrometer is about 10^9 ohms. This is at least a factor of 10^4 below the internal resistance of the detectors and connecting cables; thus, essentially all of the current produced by the detector passes into the electrometer and is measured. Measurements with the Cary electrometer are accurate to within about 1% for currents larger than 5×10^{-13} amperes.

Detector signal and background measurements were made with an unperturbed core and with 0.75- and 3-inch gaps in the pin in position 1. These measurements were taken with the rhodium, or background, detector positioned in the center calibration tube of the composite assembly. The composite assembly was rotated so that the central vertical rhodium detector in the assembly was north of the calibration tube (i.e., not between the calibration tube and the gapped pin) for each of the three cases that the detector current was measured. A fourth detector measurement was taken with a 3-inch gap in pin 1 and with the composite assembly rotated, so that the central vertical rhodium detector in the assembly was between the calibration tube and pin 1.

All of the rhodium detector measurements were taken at a reactor power level of 700 watts and a critical water height of 142.0 cm. All safety blades were fully withdrawn. The detector was allowed to come to equilibrium for at least 10 minutes after reaching power or changing detector position before recording the detector current. Owing to this long wait time per point and to an operating limitation of 60,000 watt-minutes on integrated power, each case required at least three reactor runs. A 5-inch immovable rhodium incore detector was placed in the center position of one of the outer "elements," and current readings from this detector were used to compensate the current readings from the special rhodium incore detector for small changes in power during a reactor run and from one run to another.

Figures 2-10 through 2-13 are plots of rhodium detector current versus detector position. The detector current readings from which these plots were made are given in Tables 2-3 through 2-6.

2.2.4. Measurements With Gold Foil

Fourteen gold foils, 0.259-inch diameter by 0.005-inch thick, were placed on pin 3, seven on the north side of the pin and seven on the south side. The foils were placed on the pin at 5 cm intervals starting 21.78 inches (55 cm) above the base plate and ending at 33.59 inches (85 cm). These foils were irradiated for 1 kW-min with no perturbing pins in core. Another set of foils was irradiated with a 3-inch gap in pin 2. The foils were counted for 1 minute on each side in three end-window, gas-flow proportional counters. The average of the saturated activity from these six counts is given in Table 2-7, and a plot is given in Figures 2-14 and 2-15.

2.2.5. Gold Wire Flux Measurements

Gold wires (0.020-inch diameter by 42.0 inches long) were irradiated for 1 hour in the calibration tube of the composite assembly at a power of 500 watts with a critical water height of 142.0 cm. The wires were irradiated with gaps of various sizes in various pin locations around the composite assembly. Wires were also irradiated with no perturbations in the core and with the 4 by 4 pin pitch Inconel grid in place. The wires were loaded in the end of a 0.0625-inch-OD by 0.040-inch-ID Inconel tube, which was then inserted to the bottom of the 0.093-inch-ID calibration tube.

After irradiation, the wires were cut into 0.25-inch segments from 8 inches below the center of the perturbation to 8 inches above it. Each of these 0.25-inch segments was beta-counted in three different gas-flow, end-window proportional counters. The weight of each segment was obtained, and the average saturated activity per milligram of gold was calculated. These data are tabulated in Tables 2-8 through 2-16 and plotted in Figures 2-16 through 2-24.

2.2.6. Power Profile Measurements

The relative power distribution along a fuel rod in the vicinity of a perturbation was determined by counting collimated fission product gamma rays from the activated fuel rods with an NaI(Tl) scintillation detector. Gamma photons of <350 keV energy were discriminated out. The collimator consisted of a 0.5-inch-wide by 1-inch-long slot in a 2-inch-thick lead shield placed between the

fuel rod and the detector, so that only the gammas from a 0.5-inch segment of the rod were counted. The detector was surrounded by 2 inches of lead, and other portions of the fuel rod were shielded from the detector by another 2 inches of lead.

The fuel rods were activated for 8 minutes at 125 watts with a critical water height of 142.0 cm. The activated fuel rods were counted after a 30-minute decay time. The rods were rotated while being counted to provide data that were independent of the orientation of the rod. Counting time varied from 20 to 200 seconds, and a total of approximately 80,000 counts was collected at each rod position. The fuel rods were counted every inch in the interval of 5 inches above and below the center of the perturbation and every 0.5 inch in the perturbation. The background activity was kept low by loading fuel rods with very low power histories in the positions to be studied.

Decay corrections were obtained from a "master" fuel rod, which was irradiated in the east imaginary element simultaneously with the rods to be scanned and then counted in a second counting system. The collimation and electronics of the second system were identical to those of the first. Counts were taken on the two systems simultaneously, and during the acquisition of data on a given run, the master fuel rod was never moved. A standard fuel rod was recounted at frequent intervals to provide a check for stability in the two systems.

Power profiles in fuel rods 1 through 12 were obtained with no perturbing rods in the core, with a 3-inch gap in pin 2, and with a 3-inch gap in pins 1 and 6. These data are given in Tables 2-17 through 2-27 and are plotted in Figures 2-25 through 2-35. Power profiles of fuel rods 13 through 15 were obtained with the Inconel grid on the 16-pin insert. These data are given in Table 2-28 and are plotted in Figure 2-36. The standard deviation of these data is less than 1%.

Table 2-1. Physical Properties of 2.46%-Enriched
 UO_2 Fuel Rods

Parameter	Value
Outer diameter, in.	0.4748 ± 0.0006
Wall thickness, in.	0.032 ± 0.001
Wall material	6061 aluminum
Pellet (fuel) diameter, in.	0.4054 ± 0.0005
Total length, in.	61.59 ± 0.16
Active (fuel) length, in.	60.37 ± 0.35
Weight of fuel, g/rod	1305.5 ± 1.0
U/ UO_2 , wt %	88.13 ± 0.01
Enrichment, $^{235}\text{U}/\text{U}$, wt %	2.459 ± 0.002
Weight of ^{235}U , g/rod	28.29 ± 0.02
Pellet (fuel) density, g/cm^3	10.24 ± 0.04
$\Sigma N_i \sigma_i$ (summation of impurities), cm^2/cm^3 oxide	$<10^{-3}$

Table 2-2. Special Rhodium Detector Characteristics

Overall length, ft	28.46
Outside diameter, in.	0.0625
Emitter length, in.	1.00
Emitter diameter, in.	0.0175
Emitter mass, g	0.045925
Tip to emitter distance, in.	35/64
Lead wire	
Material	Inconel 600
OD, in.	0.0095
Capacitance (lead to sheath), pF	2352
Resistance (lead to sheath), ohms	4×10^{13}

Table 2-3. Rhodium Detector Current in Unperturbed Core

Height above base plate, in.	Rh current, 10^{-12} A	Background current, ^(a) 10^{-12} A	Background corrected Rh current, 10^{-12} A
22.77	0.677	-0.132	0.809
23.66	0.682	-(0.127)	0.809
24.71	0.713	-0.122	0.835
25.72	0.727	-(0.117)	0.844
26.72	0.733	-0.112	0.845
27.71	0.734	-(0.108)	0.842
28.68	0.734	-0.104	0.838
29.65	0.737	-(0.099)	0.836
30.72	0.735	-0.093	0.828
31.72	0.734	-(0.088)	0.822
32.66	0.732	-0.082	0.814
33.66	0.732	-(0.076)	0.808
34.65	0.721	-0.070	0.791
35.63	0.716	-(0.066)	0.782
36.70	0.699	-0.062	0.761
37.69	0.674	-(0.058)	0.732
38.69	0.654	-0.053	0.707

^(a) Background currents in parentheses were obtained by interpolation.

Table 2-4. Rhodium Detector Current With 3-Inch Gap in Pin 1

Height above base plate, in.	Rh current, 10^{-12} A	Background Rh current, 10^{-12} A	Background corrected Rh current, 10^{-12} A
25.72	0.738	-0.098	0.836
26.72	0.742	-0.092	0.834
27.71	0.742	-0.090	0.832
28.68	0.762	-0.086	0.848
29.65	0.771	-0.083	0.854
30.72	0.773	-0.078	0.851
31.72	0.737	-0.074	0.811
32.66	0.736	-0.069	0.805
33.67	0.727	-0.064	0.791
34.65	0.723	-0.059	0.782
35.63	0.719	-0.057	0.776

Table 2-5. Rhodium Detector Current With 3-Inch Gap in Pin 1 and Rh Detector in Composite Assembly Facing Pin 1

Height above base plate, in.	Rh current, 10^{-12} A	Background current, 10^{-12} A	Background corrected Rh current, 10^{-12} A
25.72	0.733	-0.099	0.832
26.72	0.732	-0.097	0.829
27.71	0.736	-0.093	0.829
28.68	0.753	-0.089	0.842
29.65	0.760	-0.085	0.845
30.72	0.776	-0.080	0.856
31.72	0.752	-0.076	0.828
32.66	0.738	-0.072	0.810
33.67	0.722	-0.066	0.788
34.65	0.721	-0.062	0.783
35.63	0.719	-0.060	0.779

Table 2-6. Rhodium Detector Current
With 0.75-Inch Gap in Pin 1

Height above base plate, in.	Rh current, 10^{-12} A	Background current, 10^{-12} A	Background corrected Rh current, 10^{-12} A
27.71	0.726	-0.096	0.822
28.68	0.728	-0.093	0.821
29.20	0.736	-0.090	0.826
29.65	0.743	-0.090	0.833
30.20	0.743	-0.087	0.830
30.72	0.743	-0.084	0.827
31.72	0.729	-0.078	0.807
32.66	0.726	-0.072	0.798

Table 2-7. Saturated Activity of Gold
Foil Irradiated on Pin 3

Height above base plate, in.	Activity, count/min $\times 10^7$			
	3-inch gap in pin 2		No gaps in core	
	0 deg	180 deg	0 deg	180 deg
21.78	1.575	1.515	1.579	1.512
23.75	1.616	1.564	1.625	1.557
25.72	1.643	1.593	1.660	1.627
27.69	1.660	1.607	1.670	1.618
29.66	1.743	1.633	1.664	1.625
31.63	1.659	1.622	1.653	1.607
33.59	1.591	1.569	1.613	1.564

Table 2-8. Saturated Activity of Gold Wire With
No Gaps in Core

Interval from perturbation, in.	Activity, 10^5 counts/min	Interval from perturbation, in.	Activity, 10^5 counts/min
(-8) - (-7.75)	1.380	0.0 - 0.25	1.441
(-7.75) - (-7.50)	1.380	0.25 - 0.50	1.435
(-7.50) - (-7.25)	1.385	0.50 - 0.75	1.421
(-7.25) - (-7.0)	1.385	0.75 - 1.0	1.419
(-7.0) - (-6.75)	1.383	1.0 - 1.25	1.436
(-6.75) - (-6.50)	1.391	1.25 - 1.50	1.429
(-6.50) - (-6.25)	1.402	1.50 - 1.75	1.430
(-6.25) - (-6.0)	1.409	1.75 - 2.0	1.432
(-6.0) - (-5.75)	1.433	2.0 - 2.25	1.416
(-5.75) - (-5.50)	1.424	2.25 - 2.50	1.414
(-5.50) - (-5.25)	1.431	2.50 - 2.75	1.413
(-5.25) - (-5.0)	1.436	2.75 - 3.0	1.425
(-5.0) - (-4.75)	1.447	3.0 - 3.25	1.403
(-4.75) - (-4.50)	1.444	3.25 - 3.50	1.449
(-4.50) - (-4.25)	1.451	3.50 - 3.75	1.375
(-4.25) - (-4.0)	1.453	3.75 - 4.0	1.396
(-4.0) - (-3.75)	1.456	4.0 - 4.25	1.395
(-3.75) - (-3.50)	1.455	4.25 - 4.50	1.385
(-3.50) - (-3.25)	1.458	4.50 - 4.75	1.377
(-3.25) - (-3.0)	1.485	4.75 - 5.0	1.368
(-3.0) - (-2.75)	1.460	5.0 - 5.25	1.358
(-2.75) - (-2.50)	1.444	5.25 - 5.50	1.364
(-2.50) - (-2.25)	1.445	5.50 - 5.75	1.344
(-2.25) - (-2.0)	1.447	5.75 - 6.0	1.339
(-2.0) - (-1.75)	1.459	6.0 - 6.25	1.352
(-1.75) - (-1.50)	1.443	6.25 - 6.50	1.326
(-1.50) - (-1.25)	1.448	6.50 - 6.75	1.306
(-1.25) - (-1.0)	1.434	6.75 - 7.0	1.304
(-1.0) - (-0.75)	1.436	7.0 - 7.25	1.314
(-0.75) - (-0.50)	1.419	7.25 - 7.50	1.293
(-0.50) - (-0.25)	1.433	7.50 - 7.75	1.277
(-0.25) - 0.0	1.432	7.75 - 8.0	1.264

Table 2-9. Saturated Activity of Gold Wire With
3-Inch Gap in Pin 1

Interval from perturbation, in.	Activity, 10^5 counts/min	Interval from perturbation, in.	Activity, 10^5 counts/min
(-8) - (-7.75)	1.388	0.0 - 0.25	1.490
(-7.75) - (-7.50)	1.398	0.25 - 0.50	1.499
(-7.50) - (-7.25)	1.401	0.50 - 0.75	1.486
(-7.25) - (-7.0)	1.392	0.75 - 1.0	1.477
(-7.0) - (-6.75)	1.402	1.0 - 1.25	1.455
(-6.75) - (-6.50)	1.411	1.25 - 1.50	1.432
(-6.50) - (-6.25)	1.421	1.50 - 1.75	1.440
(-6.25) - (-6.0)	1.436	1.75 - 2.0	1.440
(-6.0) - (-5.75)	1.429	2.0 - 2.25	1.423
(-5.75) - (-5.50)	1.444	2.25 - 2.50	1.425
(-5.50) - (-5.25)	1.446	2.50 - 2.75	1.422
(-5.25) - (-5.0)	1.427	2.75 - 3.0	1.417
(-5.0) - (-4.75)	1.425	3.0 - 3.25	1.412
(-4.75) - (-4.50)	1.462	3.25 - 3.50	1.373
(-4.50) - (-4.25)	1.452	3.50 - 3.75	1.382
(-4.25) - (-4.0)	1.445	3.75 - 4.0	1.378
(-4.0) - (-3.75)	1.452	4.0 - 4.25	1.419
(-3.75) - (-3.50)	1.458	4.25 - 4.50	1.374
(-3.50) - (-3.25)	1.458	4.50 - 4.75	1.395
(-3.25) - (-3.0)	1.442	4.75 - 5.0	1.398
(-3.0) - (-2.75)	1.433	5.0 - 5.25	1.333
(-2.75) - (-2.50)	1.458	5.25 - 5.50	1.374
(-2.50) - (-2.25)	1.432	5.50 - 5.75	1.356
(-2.25) - (-2.0)	1.435	5.75 - 6.0	1.340
(-2.0) - (-1.75)	1.470	6.0 - 6.25	1.342
(-1.75) - (-1.50)	1.483	6.25 - 6.50	1.315
(-1.50) - (-1.25)	1.488	6.50 - 6.75	1.316
(-1.25) - (-1.0)	1.494	6.75 - 7.0	1.309
(-1.0) - (-0.75)	1.507	7.0 - 7.25	1.313
(-0.75) - (-0.50)	1.515	7.25 - 7.50	1.279
(-0.50) - (-0.25)	1.501	7.50 - 7.75	1.277
(-0.25) - 0.0	1.484	7.75 - 8.0	1.253

Table 2-10. Saturated Activity of Gold Wire With 3-Inch Gap in Pin 1 and Composite Assembly Rotated so That Central Vertical Rhodium Detector is South of Calibration Tube

Interval from perturbation, in.	Activity, 10 ⁵ counts/min	Interval from perturbation, in.	Activity, 10 ⁵ counts/min
(-8) - (-7.75)	1.368	0.0 - 0.35	1.488
(-7.75) - (-7.50)	1.354	0.25 - 0.50	1.479
(-7.50) - (-7.25)	1.386	0.50 - 0.75	1.482
(-7.25) - (-7.0)	1.385	0.75 - 1.0	1.484
(-7.0) - (-6.75)	1.382	1.0 - 1.25	1.462
(-6.75) - (-6.50)	1.406	1.25 - 1.50	1.452
(-6.50) - (-6.25)	1.417	1.50 - 1.75	1.430
(-6.25) - (-6.0)	1.419	1.75 - 2.0	1.439
(-6.0) - (-5.75)	1.421	2.0 - 2.25	1.427
(-5.75) - (-5.50)	1.440	2.25 - 2.50	1.400
(-5.50) - (-5.25)	1.443	2.50 - 2.75	1.418
(-5.25) - (-5.0)	1.431	2.75 - 3.0	1.411
(-5.0) - (-4.75)	1.450	3.0 - 3.25	1.406
(-4.75) - (-4.50)	1.434	3.25 - 3.50	1.359
(-4.50) - (-4.25)	1.439	3.50 - 3.75	1.362
(-4.25) - (-4.0)	1.461	3.75 - 4.0	1.371
(-4.0) - (-3.75)	1.456	4.0 - 4.25	1.384
(-3.75) - (-3.50)	1.452	4.25 - 4.50	1.336
(-3.50) - (-3.25)	1.444	4.50 - 4.75	1.375
(-3.25) - (-3.0)	1.444	4.75 - 5.0	1.362
(-3.0) - (-2.75)	1.444	5.0 - 5.25	1.362
(-2.75) - (-2.50)	1.450	5.25 - 5.50	1.351
(-2.50) - (-2.25)	1.454	5.50 - 5.75	1.355
(-2.25) - (-2.0)	1.447	5.75 - 6.0	1.334
(-2.0) - (-1.75)	1.449	6.0 - 6.25	1.288
(-1.75) - (-1.50)	1.462	6.25 - 6.50	1.322
(-1.50) - (-1.25)	1.464	6.50 - 6.75	1.288
(-1.25) - (-1.0)	1.464	6.75 - 7.0	1.286
(-1.0) - (-0.75)	1.479	7.0 - 7.25	1.280
(-0.75) - (-0.50)	1.480	7.25 - 7.50	1.300
(-0.50) - (-0.25)	1.474	7.50 - 7.75	1.267
(-0.25) - 0.0	1.478	7.75 - 8.0	1.263

Table 2-11. Saturated Gold Wire Activity With
3-Inch Collapsed Gap in Pin 1

Interval from perturbation, in.	Activity, 10 ⁵ counts/min	Interval from perturbation, in.	Activity, 10 ⁵ counts/min
(-8) - (-7.75)	1.402	0.0 - 0.25	1.494
(-7.75) - (-7.50)	1.386	0.25 - 0.50	1.495
(-7.50) - (-7.25)	1.405	0.50 - 0.75	1.474
(-7.25) - (-7.0)	1.395	0.75 - 1.0	1.467
(-7.0) - (-6.75)	1.410	1.0 - 1.25	1.466
(-6.75) - (-6.50)	1.426	1.25 - 1.50	1.457
(-6.50) - (-6.25)	1.415	1.50 - 1.75	1.440
(-6.25) - (-6.0)	1.426	1.75 - 2.0	1.420
(-6.0) - (-5.75)	1.437	2.0 - 2.25	1.412
(-5.75) - (-5.50)	1.426	2.25 - 2.50	1.385
(-5.50) - (-5.25)	1.440	2.50 - 2.75	1.382
(-5.25) - (-5.0)	1.443	2.75 - 3.0	1.372
(-5.0) - (-4.75)	1.446	3.0 - 3.25	1.372
(-4.75) - (-4.50)	1.441	3.25 - 3.50	1.377
(-4.50) - (-4.25)	1.439	3.50 - 3.75	1.365
(-4.25) - (-4.0)	1.456	3.75 - 4.0	1.361
(-4.0) - (-3.75)	1.439	4.0 - 4.25	1.363
(-3.75) - (-3.50)	1.433	4.25 - 4.50	1.350
(-3.50) - (-3.25)	1.428	4.50 - 4.75	1.353
(-3.25) - (-3.0)	1.422	4.75 - 5.0	1.341
(-3.0) - (-2.75)	1.431	5.0 - 5.25	1.323
(-2.75) - (-2.50)	1.435	5.25 - 5.50	1.319
(-2.50) - (-2.25)	1.440	5.50 - 5.75	1.300
(-2.25) - (-2.0)	1.445	5.75 - 6.0	1.285
(-2.0) - (-1.75)	1.460	6.0 - 6.25	1.294
(-1.75) - (-1.50)	1.457	6.25 - 6.50	1.286
(-1.50) - (-1.25)	1.469	6.50 - 6.75	1.269
(-1.25) - (-1.0)	1.475	6.75 - 7.0	1.260
(-1.0) - (-0.75)	1.491	7.0 - 7.25	1.257
(-0.75) - (-0.50)	1.514	7.25 - 7.50	1.258
(-0.50) - (-0.25)	1.501	7.50 - 7.75	1.231
(-0.25) - 0.0	1.484	7.75 - 8.0	1.222

Table 2-12. Saturated Activity of Gold Wire With
3-Inch Gap in Pin 2

Interval from perturbation, in.	Activity, 10^5 counts/min	Interval from perturbation, in.	Activity, 10^5 counts/min
(-8) - (-7.75)	1.387	0.0 - 0.25	1.438
(-7.75) - (-7.50)	1.388	0.25 - 0.50	1.428
(-7.50) - (-7.25)	1.398	0.50 - 0.75	1.442
(-7.25) - (-7.0)	1.408	0.75 - 1.0	1.440
(-7.0) - (-6.75)	1.408	1.0 - 1.25	1.412
(-6.75) - (-6.50)	1.409	1.25 - 1.50	1.412
(-6.50) - (-6.25)	1.420	1.50 - 1.75	1.406
(-6.25) - (-6.0)	1.423	1.75 - 2.0	1.419
(-6.0) - (-5.75)	1.432	2.0 - 2.25	1.410
(-5.75) - (-5.50)	1.446	2.25 - 2.50	1.338
(-5.50) - (-5.25)	1.445	2.50 - 2.75	1.409
(-5.25) - (-5.0)	1.436	2.75 - 3.0	1.407
(-5.0) - (-4.75)	1.440	3.0 - 3.25	1.392
(-4.75) - (-4.50)	1.436	3.25 - 3.50	1.372
(-4.50) - (-4.25)	1.452	3.50 - 3.75	1.369
(-4.25) - (-4.0)	1.447	3.75 - 4.0	1.379
(-4.0) - (-3.75)	1.451	4.0 - 4.25	1.262
(-3.75) - (-3.50)	1.454	4.25 - 4.50	1.378
(-3.50) - (-3.25)	1.458	4.50 - 4.75	1.385
(-3.25) - (-3.0)	1.465	4.75 - 5.0	1.358
(-3.0) - (-2.75)	1.448	5.0 - 5.25	1.356
(-2.75) - (-2.50)	1.458	5.25 - 5.50	1.359
(-2.50) - (-2.25)	1.469	5.50 - 5.75	1.217
(-2.25) - (-2.0)	1.428	5.75 - 6.0	1.335
(-2.0) - (-1.75)	1.426	6.0 - 6.25	1.320
(-1.75) - (-1.50)	1.440	6.25 - 6.50	1.306
(-1.50) - (-1.25)	1.426	6.50 - 6.75	1.299
(-1.25) - (-1.0)	1.447	6.75 - 7.0	1.300
(-1.0) - (-0.75)	1.440	7.0 - 7.25	1.280
(-0.75) - (-0.50)	1.432	7.25 - 7.50	1.273
(-0.50) - (-0.25)	1.443	7.50 - 7.75	1.272
(-0.25) - 0.0	1.514	7.75 - 8.0	1.268

Table 2-13. Saturated Gold Wire Activity With
3-Inch Gap in Pin 7

Interval from perturbation, in.	Activity, 10^5 counts/min	Interval from perturbation, in.	Activity, 10^5 counts/min
(-8) - (-7.75)	1.414	0.0 - 0.25	1.509
(-7.75) - (-7.50)	1.389	0.25 - 0.50	1.491
(-7.50) - (-7.25)	1.413	0.50 - 0.75	1.473
(-7.25) - (-7.0)	1.408	0.75 - 1.0	1.446
(-7.0) - (-6.75)	1.415	1.0 - 1.25	1.438
(-6.75) - (-6.50)	1.428	1.25 - 1.50	1.445
(-6.50) - (-6.25)	1.429	1.50 - 1.75	1.433
(-6.25) - (-6.0)	1.438	1.75 - 2.0	1.422
(-6.0) - (-5.75)	1.439	2.0 - 2.25	1.416
(-5.75) - (-5.50)	1.470	2.25 - 2.50	1.424
(-5.50) - (-5.25)	1.446	2.50 - 2.75	1.417
(-5.25) - (-5.0)	1.444	2.75 - 3.0	1.420
(-5.0) - (-4.75)	1.463	3.0 - 3.25	1.397
(-4.75) - (-4.50)	1.449	3.25 - 3.50	1.385
(-4.50) - (-4.25)	1.467	3.50 - 3.75	1.373
(-4.25) - (-4.0)	1.495	3.75 - 4.0	1.399
(-4.0) - (-3.75)	1.497	4.0 - 4.25	1.397
(-3.75) - (-3.50)	1.479	4.25 - 4.50	1.383
(-3.50) - (-3.25)	1.492	4.50 - 4.75	1.395
(-3.25) - (-3.0)	1.476	4.75 - 5.0	1.378
(-3.0) - (-2.75)	1.485	5.0 - 5.25	1.385
(-2.75) - (-2.50)	1.396	5.25 - 5.50	1.351
(-2.50) - (-2.25)	1.555	5.50 - 5.75	1.366
(-2.25) - (-2.0)	1.479	5.75 - 6.0	1.352
(-2.0) - (-1.75)	1.468	6.0 - 6.25	1.333
(-1.75) - (-1.50)	1.475	6.25 - 6.50	1.345
(-1.50) - (-1.25)	1.465	6.50 - 6.75	1.321
(-1.25) - (-1.0)	1.496	6.75 - 7.0	1.295
(-1.0) - (-0.75)	1.477	7.0 - 7.25	1.296
(-0.75) - (-0.50)	1.471	7.25 - 7.50	1.278
(-0.50) - (-0.25)	1.479	7.50 - 7.75	1.286
(-0.25) - 0.0	1.470	7.75 - 8.0	1.259

Table 2-14. Saturated Gold Wire Activity With
1.5-Inch Gap in Pin 1

Interval from perturbation, in.	Activity, 10 ⁵ counts/min	Interval from perturbation, in.	Activity, 10 ⁵ counts/min
(-8) - (-7.75)	1.404	0.0 - 0.25	1.483
(-7.75) - (-7.50)	1.398	0.25 - 0.50	1.470
(-7.50) - (-7.25)	1.411	0.50 - 0.75	1.475
(-7.25) - (-7.0)	1.414	0.75 - 1.0	1.452
(-7.0) - (-6.75)	1.421	1.0 - 1.25	1.450
(-6.75) - (-6.50)	1.430	1.25 - 1.50	1.430
(-6.50) - (-6.25)	1.421	1.50 - 1.75	1.436
(-6.25) - (-6.0)	1.434	1.75 - 2.0	1.428
(-6.0) - (-5.75)	1.445	2.0 - 2.25	1.411
(-5.75) - (-5.50)	1.447	2.25 - 2.50	1.413
(-5.50) - (-5.25)	1.450	2.50 - 2.75	1.428
(-5.25) - (-5.0)	1.454	2.75 - 3.0	1.409
(-5.0) - (-4.75)	1.459	3.0 - 3.25	1.424
(-4.75) - (-4.50)	1.464	3.25 - 3.50	1.389
(-4.50) - (-4.25)	1.454	3.50 - 3.75	1.384
(-4.25) - (-4.0)	1.458	3.75 - 4.0	1.394
(-4.0) - (-3.75)	1.467	4.0 - 4.25	1.385
(-3.75) - (-3.50)	1.458	4.25 - 4.50	1.394
(-3.50) - (-3.25)	1.460	4.50 - 4.75	1.392
(-3.25) - (-3.0)	1.473	4.75 - 5.0	1.381
(-3.0) - (-2.75)	1.474	5.0 - 5.25	1.378
(-2.75) - (-2.50)	1.466	5.25 - 5.50	1.357
(-2.50) - (-2.25)	1.462	5.50 - 5.75	1.364
(-2.25) - (-2.0)	1.469	5.75 - 6.0	1.354
(-2.0) - (-1.75)	1.449	6.0 - 6.25	1.339
(-1.75) - (-1.50)	1.430	6.25 - 6.50	1.315
(-1.50) - (-1.25)	1.472	6.50 - 6.75	1.317
(-1.25) - (-1.0)	1.483	6.75 - 7.0	1.309
(-1.0) - (-0.75)	1.470	7.0 - 7.25	1.292
(-0.75) - (-0.50)	1.495	7.25 - 7.50	1.296
(-0.50) - (-0.25)	1.479	7.50 - 7.75	1.289
(-0.25) - 0.0	1.486	7.75 - 8.0	1.294

Table 2-15. Saturated Gold Wire Activity With
0.75-Inch Gap in Pin 1

Interval from perturbation, in.	Activity, 10 ⁵ counts/min	Interval from perturbation, in.	Activity, 10 ⁵ counts/min
(-8) - (-7.75)	1.393	0.0 - 0.25	1.440
(-7.75) - (-7.50)	1.399	0.25 - 0.50	1.423
(-7.50) - (-7.25)	1.399	0.50 - 0.75	1.440
(-7.25) - (-7.0)	1.402	0.75 - 1.0	1.421
(-7.0) - (-6.75)	1.403	1.0 - 1.25	1.417
(-6.75) - (-6.50)	1.428	1.25 - 1.50	1.427
(-6.50) - (-6.25)	1.417	1.50 - 1.75	1.412
(-6.25) - (-6.0)	1.431	1.75 - 2.0	1.405
(-6.0) - (-5.75)	1.439	2.0 - 2.25	1.409
(-5.75) - (-5.50)	1.451	2.25 - 2.50	1.405
(-5.50) - (-5.25)	1.447	2.50 - 2.75	1.418
(-5.25) - (-5.0)	1.446	2.75 - 3.0	1.390
(-5.0) - (-4.75)	1.445	3.0 - 3.25	1.346
(-4.75) - (-4.50)	1.461	3.25 - 3.50	1.359
(-4.50) - (-4.25)	1.455	3.50 - 3.75	1.372
(-4.25) - (-4.0)	1.470	3.75 - 4.0	1.378
(-4.0) - (-3.75)	1.455	4.0 - 4.25	1.379
(-3.75) - (-3.50)	1.446	4.25 - 4.50	1.377
(-3.50) - (-3.25)	1.440	4.50 - 4.75	1.397
(-3.25) - (-3.0)	1.459	4.75 - 5.0	1.378
(-3.0) - (-2.75)	1.449	5.0 - 5.25	1.368
(-2.75) - (-2.50)	1.444	5.25 - 5.50	1.355
(-2.50) - (-2.25)	1.442	5.50 - 5.75	1.351
(-2.25) - (-2.0)	1.439	5.75 - 6.0	1.342
(-2.0) - (-1.75)	1.448	6.0 - 6.25	1.340
(-1.75) - (-1.50)	1.434	6.25 - 6.50	1.314
(-1.50) - (-1.25)	1.439	6.50 - 6.75	1.327
(-1.25) - (-1.0)	1.445	6.75 - 7.0	1.294
(-1.0) - (-0.75)	1.453	7.0 - 7.25	1.287
(-0.75) - (-0.50)	1.448	7.25 - 7.50	1.282
(-0.50) - (-0.25)	1.445	7.50 - 7.75	1.279
(-0.25) - 0.0	1.439	7.75 - 8.0	1.258

**Table 2-16. Saturated Activity of Gold Wire With
4 by 4 Pin Pitch Inconel Grid in Core**

<u>Interval from perturbation, in.</u>	<u>Activity, 10⁵ counts/min</u>	<u>Interval from perturbation, in.</u>	<u>Activity, 10⁵ counts/min</u>
(-8) - (-7.75)	1.359	0.0 - 0.25	1.354
(-7.75) - (-7.50)	1.384	0.25 - 0.50	1.343
(-7.50) - (-7.25)	1.393	0.50 - 0.75	1.348
(-7.25) - (-7.0)	1.411	0.75 - 1.0	1.369
(-7.0) - (-6.75)	1.405	1.0 - 1.25	1.392
(-6.75) - (-6.50)	1.394	1.25 - 1.50	1.395
(-6.50) - (-6.25)	1.419	1.50 - 1.75	1.408
(-6.25) - (-6.0)	1.424	1.75 - 2.0	1.426
(-6.0) - (-5.75)	1.436	2.0 - 2.25	1.428
(-5.75) - (-5.50)	1.424	2.25 - 2.50	1.433
(-5.50) - (-5.25)	1.443	2.50 - 2.75	1.435
(-5.25) - (-5.0)	1.434	2.75 - 3.0	1.424
(-5.0) - (-4.75)	1.460	3.0 - 3.25	1.414
(-4.75) - (-4.50)	1.461	3.25 - 3.50	1.403
(-4.50) - (-4.25)	1.455	3.50 - 3.75	1.390
(-4.25) - (-4.0)	1.458	3.75 - 4.0	1.414
(-4.0) - (-3.75)	1.470	4.0 - 4.25	1.390
(-3.75) - (-3.50)	1.464	4.25 - 4.50	1.392
(-3.50) - (-3.25)	1.476	4.50 - 4.75	1.385
(-3.25) - (-3.0)	1.461	4.75 - 5.0	1.387
(-3.0) - (-2.75)	1.470	5.0 - 5.25	1.375
(-2.75) - (-2.50)	1.458	5.25 - 5.50	1.365
(-2.50) - (-2.25)	1.442	5.50 - 5.75	1.357
(-2.25) - (-2.0)	1.445	5.75 - 6.0	1.337
(-2.0) - (-1.75)	1.446	6.0 - 6.25	1.322
(-1.75) - (-1.50)	1.417	6.25 - 6.50	1.330
(-1.50) - (-1.25)	1.437	6.50 - 6.75	1.324
(-1.25) - (-1.0)	1.417	6.75 - 7.0	1.342
(-1.0) - (-0.75)	1.407	7.0 - 7.25	1.313
(-0.75) - (-0.50)	1.382	7.25 - 7.50	1.306
(-0.50) - (-0.25)	1.370	7.50 - 7.75	1.293
(-0.25) - 0.0	1.356	7.75 - 8.0	1.281

Table 2-17. Pin 1 Relative Power Density

<u>Height, in.</u>	<u>No gap</u>	<u>3-in. gap in pin 2</u>
5	1.027	1.029
4	1.022	1.035
3	1.028	1.036
2	1.023	1.039
1.5	--	1.059
1	1.034	1.062
0.5	--	1.068
0	1.032	1.063
0.5	--	1.061
1	1.020	1.053
1.5	--	1.043
2	1.014	1.028
3	0.994	0.995
4	0.988	0.985
5	0.973	0.971

Table 2-18. Pin 2 Relative Power Density

<u>Height, in.</u>	<u>No gap</u>	<u>3-in. gap in pins 1 and 6</u>
-5	1.026	1.017
-4	1.039	1.030
-3	1.041	1.042
-2	1.036	1.063
-1.5	--	1.063
-1	1.040	1.078
-0.5	--	1.088
0	1.036	1.089
0.5	--	1.078
1	1.032	1.064
1.5	--	1.064
2	1.031	1.040
3	1.006	1.019
4	0.991	1.000
5	0.974	0.983

Table 2-19. Pin 3 Relative Power Density

<u>Height, in.</u>	<u>No gap</u>	<u>3-in. gap in pin 2</u>	<u>3-in. gap in pins 1 and 6</u>
-5	1.019	1.020	1.019
-4	1.029	1.029	1.031
-3	1.033	1.035	1.045
-2	1.037	1.047	1.037
-1.5	--	1.070	1.043
-1	1.041	1.082	1.042
-0.5	--	1.082	1.046
0	1.036	1.090	1.041
0.5	--	1.082	1.040
1	1.023	1.079	1.036
1.5	--	1.048	1.022
2	1.012	1.034	1.023
3	1.003	1.008	1.000
4	0.990	1.986	1.994
5	0.981	0.980	0.981

Table 2-20. Pin 4 Relative Power Density

<u>Height, in.</u>	<u>No gap</u>	<u>3-in. gap in pin 2</u>	<u>3-in. gap in pins 1 and 6</u>
-5	1.039	1.025	1.034
-4	1.040	1.027	1.046
-3	1.040	1.029	1.046
-2	1.040	1.030	1.043
-1.5	--	1.029	1.041
-1	1.041	1.034	1.038
-0.5	--	1.037	1.047
0	1.029	1.034	1.041
0.5	--	1.030	1.036
1	1.024	1.025	1.032
1.5	--	1.025	1.033
2	1.010	1.014	1.029
3	1.005	0.994	1.004
4	0.974	0.979	0.987
5	0.961	0.975	0.966

Table 2-21. Pin 5 Relative Power Density

<u>Height, in.</u>	<u>No gap</u>	<u>3-in. gap in pin 2</u>
-5	1.026	1.036
-4	1.043	1.043
-3	1.034	1.058
-2	1.040	1.055
-1.5	--	1.052
-1	1.036	1.053
-0.5	--	1.063
0	1.029	1.040
0.5	--	1.052
1	1.024	1.035
1.5	--	1.030
2	1.021	1.021
3	1.002	1.009
4	0.999	0.986
5	0.974	0.964

Table 2-22. Pin 7 Relative Power Density

<u>Height, in.</u>	<u>No gap</u>	<u>3-in. gap in pin 2</u>	<u>3-in. gap in pins 1 and 6</u>
-5	1.034	1.023	1.029
-4	1.047	1.038	1.044
-3	1.041	1.039	1.054
-2	1.051	1.053	1.075
-1.5	--	1.053	1.101
-1	1.034	1.062	1.128
-0.5	--	1.061	1.128
0	1.035	1.069	1.121
0.5	--	1.065	1.124
1	1.023	1.050	1.099
1.5	--	1.039	1.077
2	1.026	1.027	1.067
3	1.007	1.007	1.023
4	0.989	0.993	1.000
5	0.966	0.977	0.971
6	0.966		

Table 2-23. Pin 8 Relative Power Density

<u>Height, in.</u>	<u>No gap</u>	<u>3-in. gap in pin 2</u>	<u>3-in. gap in pins 1 and 6</u>
-5	1.019	1.028	1.023
-4	1.028	1.034	1.048
-3	1.030	1.045	1.039
-2	1.035	1.054	1.047
-1.5	--	1.056	1.056
-1	1.031	1.069	1.058
-0.5	--	1.084	1.069
0	1.037	1.096	1.060
0.5	--	1.075	1.060
1	1.017	1.069	1.055
1.5	--	1.053	1.047
2	1.011	1.030	1.019
3	1.012	1.013	1.007
4	0.983	0.992	0.998
5	0.981	0.972	0.977

Table 2-24. Pin 9 Relative Power Density

<u>Height, in.</u>	<u>No gap</u>	<u>3-in. gap in pin 2</u>	<u>3-in. gap in pins 1 and 6</u>
-5	1.027	1.020	1.018
-4	1.021	1.034	1.013
-3	1.029	1.038	1.024
-2	1.042	1.048	1.030
-1.5	--	1.049	1.031
-1	1.032	1.043	1.035
-0.5	--	1.053	1.039
0	1.027	1.049	1.033
0.5	--	1.054	1.039
1	1.018	1.042	1.035
1.5	--	1.043	1.016
2	1.003	1.025	1.009
3	1.000	1.009	1.006
4	0.987	0.994	0.989
5	0.973	0.980	0.982

Table 2-25. Pin 10 Relative Power Density

<u>Height, in.</u>	<u>No gap</u>	<u>3-in. gap in pin 2</u>
-5	1.025	1.024
-4	1.037	1.030
-3	1.046	1.027
-2	1.036	1.035
-1.5	--	1.036
-1	1.032	1.032
-0.5	--	1.038
0	1.030	1.039
0.5	--	1.039
1	1.022	1.028
1.5	--	1.023
2	1.020	1.020
3	0.994	1.006
4	0.991	0.983
5	0.975	0.976

Table 2-26. Pin 11 Relative Power Density

<u>Height, in.</u>	<u>No gap</u>	<u>3 in. gap in pin 2</u>	<u>3-in. gap in pins 1 and 6</u>
-5	1.025	1.023	1.029
-4	1.022	1.027	1.035
-3	1.034	1.037	1.043
-2	1.040	1.038	1.034
-1.5	--	1.047	1.041
-1	1.021	1.043	1.036
-0.5	--	1.039	1.031
0	1.023	1.031	1.037
0.5	--	1.029	1.018
1	1.026	1.031	1.028
1.5	--	1.027	1.022
2	1.013	1.015	1.015
3	1.005	0.994	1.006
4	0.989	0.996	0.986
5	0.975	0.977	0.971

Table 2-27. Pin 12 Relative Power Density

<u>Height, in.</u>	<u>No gap</u>	<u>3-in. gap in pin 2</u>
-5	1.021	1.020
-4	1.043	1.034
-3	1.034	1.041
-2	1.040	1.037
-1.5	--	1.036
-1	1.037	1.041
-0.5	--	1.047
0	1.020	1.039
0.5	--	1.031
1	1.032	1.029
1.5	--	1.022
2	1.020	1.019
3	1.017	1.009
4	0.997	0.995
5	0.979	0.980

**Table 2-28. Relative Power Profile of Pins 13, 14, and 15
With 4 by 4 Pin Pitch Inconel Grid in Core**

<u>Distance from center of grid, in.</u>	<u>Relative power density</u>		
	<u>Pin 13</u>	<u>Pin 14</u>	<u>Pin 15</u>
-5	1.037	1.028	1.037
-4	1.032	1.031	1.031
-3	1.033	1.034	1.029
-2	1.015	1.027	1.030
-1.5	1.012	1.011	1.017
-1	0.990	1.005	0.997
-0.75	0.982	0.996	0.986
-0.5	0.969	0.983	0.970
-0.25	0.953	0.965	0.960
0	0.952	0.965	0.947
0.25	0.950	0.963	0.947
0.5	0.959	0.969	0.950
0.75	0.971	0.975	0.962
1	0.981	1.002	0.974
1.5	0.996	1.011	0.996
2	1.002	1.004	1.005
3	0.993	0.999	1.000
4	0.987	0.986	0.992
5	0.969	0.982	0.974
6	0.963	0.971	0.963

Figure 2-1. Gapped Fuel Rod and Spacer

Figure 2-2. Collapsed Fuel Rod

(All dimensions in inches)

Figure 2-3. Composite Detector Assembly

Figure 2-4. Vertical Core Dimensions

Figure 2-5. Core XII, Loading 3

- – Water Filled Position
- – Composite Detector Assembly
- X – Void Filled Inconel Tube

— North

Figure 2-7. Special Rhodium Incore Detector

Figure 2-8. Detector Drive System

Figure 2-9. Cary 401 Electrometer Diagram

Figure 2-10. Rhodium Detector Current in Unperturbed Core

Figure 2-11. Rhodium Detector Current With 3-Inch Gap in Pin 1

Figure 2-12. Rhodium Detector Current With 3-Inch Gap in Pin 1 and Rhodium Detector in Composite Assembly Facing Pin 1

Figure 2-13. Rhodium Detector Current With 0.75-Inch Gap in Pin 1

Figure 2-14. Saturated Activity of Gold Foil on Pin 3
With No Core Gap

Figure 2-15. Saturated Activity of Gold Foil on Pin 3 With 3-Inch Gap in Pin 2

Figure 2-16. Saturated Activity of 0.25-Inch Gold Wire With No Gap in Core

Figure 2-17. Saturated Activity of 0.25-Inch Gold Wire With 3-Inch Gap in Pin 1

Figure 2-18. Saturated Activity of 0.25-Inch Gold Wire With 3-Inch Gap in Pin 1 and Composite Assembly Rotated so That Rhodium Detector is South

Figure 2-19. Saturated Activity of Gold Wire With 3-Inch Collapsed Gap in Pin 1

Figure 2-20. Saturated Activity of 0.25-Inch Gold Wire With 3-Inch Gap In Pin 2

Figure 2-21. Saturated Activity of Gold Wire With 3-Inch Gap In Pin 7

Figure 2-22. Saturated Activity of 0.25-Inch Gold Wire With 1.5-Inch Gap In Pin 1

Figure 2-23. Saturated Activity of Gold Wire With 0.75-Inch Gap in Pin 1

Figure 2-24. Saturated Activity of 0.25-Inch Gold Wire With 4 by 4
Pin Pitch Inconel Grid In Core

Figure 2-25. Pin 1 Power Profile

Figure 2-26. Pin 2 Power Profile

Figure 2-27. Pin 3 Power Profile

Figure 2-28. Pin 4 Power Profile

Figure 2-29. Pin 5 Power Profile

Figure 2-30. Pin 7 Power Profile

Figure 2-31. Pin 8 Power Profile

Figure 2-32. Pin 9 Power Profile

Figure 2-33. Pin 10 Power Profile

Figure 2-34. Pin 11 Power Profile

Figure 2-35. Pin 12 Power Profile

Figure 2-36. Power Profile of Pins 13, 14, and 15 With 4 by 4 Pin Pitch Inconel Grid in Core

3. TASK 9 - CAPTURE MEASUREMENTS (H. W. Webb, M. N. Baldwin)

3.1. Introduction

The objective of Task 9 was to obtain experimental measurements of the fission rate in UO_2 fuel and to compare it with the neutron absorption rate in the boron of simulated lumped burnable poison (LBP). The results can serve to check analytical techniques used to design large PWRs.

3.2. Description of Assemblies

3.2.1. Facility and Fuel

The facility and the regular fuel rods are the same as those used in Task 8 and described in section 2.

3.2.2. Special Fuel Rod

A special fuel rod, which can be disassembled for removal of a sample fuel pellet, is also available. Sample fuel pellets irradiated in this rod were used to determine local power densities. A typical fuel rod cross section is illustrated in Figure 3-1.

3.2.3. Simulated Lumped Burnable Poison Pins

Two sizes of LBP pins have been prepared. The bottom end of each pin has a tight-fitting aluminum plug 0.5 inch thick sealed in place with epoxy; each top is sealed in place with a cork plug and epoxy. Powdered sodium tetrafluoroborate ($NaBF_4$) serves as the poison material and forms a column in each pin long enough to span the full core height.

3.2.3.1. Thick-Walled Poison Pins

The thick-walled poison pins are 0.438-inch-OD by 0.120-inch-wall tubes of 6061 aluminum. Each pin contains 55.9 ± 1.1 g of powdered $NaBF_4$, which constitutes a column 174.0 cm high.

3.2.3.2. Thin-Walled Poison Pins

The thin-walled poison pins are 0.438-inch-OD by 0.035-inch-wall tubes of 6061 aluminum. Each pin contains 195.3 ± 1.5 g of powdered NaBF_4 , which constitutes a column 174.0 cm high..

3.2.3.3. Sample Pins

Special poison pins of both the thick- and thin-walled varieties were prepared so that they could be disassembled for easy removal of a sample of poison material (see Figure 3-2.). The NaBF_4 samples of these pins were packed to an average density of 1.62 g/cm^3 .

3.2.4. Core Description

The core configuration for this task (Figure 3-3) roughly approximates a cylindrical core 51 inches in diameter and 60.4 inches high. Its grid spacing, outer boundaries, and structural components are identical to those used in Task 8 (described in section 2).

The core contains 4806 fuel rods, 16 simulated LBP pins, nine Inconel tubes, four safety blades, and one auxiliary control rod. Imaginary lines, as shown in Figure 3-3, divide the core into nine 15 by 15 arrays or "elements," each having 208 fuel rods. At the center of each element is a voided Inconel 600 tube, 0.25-inch OD by 0.035-inch wall.

3.3. Theory

This task was initiated to measure the fission rate in UO_2 fuel at selected positions within the critical assembly and to compare it with the neutron absorption rate in a simulated LBP material placed in other selected locations. The method being applied to this work relates the molybdenum-99 fission product activity in an irradiated fuel sample to the fission rate and the sodium-24 activity in an irradiated simulated LBP material to the total neutron absorption rate in that material. Absolute counting can be avoided by measuring under identical counting conditions the molybdenum-99 and sodium-24 activity from samples of identical composition irradiated in a highly thermal neutron flux for which the ratio of fission rate to absorption rate is known.

Sodium tetrafluoroborate (NaBF_4) was chosen to simulate an LBP material for several reasons:-

1. The sodium of the compound will activate and thus provide a quantitative measure of absorption rate.
2. The sodium and boron are uniformly dispersed throughout the material.
3. The absorption cross section curves for sodium and boron have a similar shape up to a neutron energy of several keV.

If we designate the fission rate in a specified fuel sample by F , then

$$F = K_1 M \frac{1 + \delta_{238}}{1 + \frac{Y_{238}}{Y_{235}} \delta_{238}} \quad (3-1)$$

where

K_1 = proportionality constant,

M = relative saturated activity of ^{99}Mo in irradiated fuel sample,

Y_{235} = ^{99}Mo yield from ^{235}U fission,

Y_{238} = ^{99}Mo yield from ^{238}U fission,

δ_{238} = ^{238}U to ^{235}U fission ratio.

The fission rate is almost directly proportional to the production rate of the fission product molybdenum-99. The slight deviation from direct proportionality is easily corrected since approximate values for Y_{235} , Y_{238} , and δ_{238} are available.^{9,15-17}

If we designate the neutron absorption rate of boron in a specified sodium NaBF_4 sample by A , then

$$A = K_2 \theta S \quad (3-2)$$

where

K_2 = proportionality constant,

S = relative saturated activity of ^{24}Na in irradiated LBP sample,

θ = calculated correction factor (approximately unity), which adjusts the results for the slight difference in absorption cross section shape of sodium and ^{10}B .

Combining equations 3-1 and 3-2,

$$\frac{P}{A} = \frac{K_3 M (1 + \delta_{238})}{\theta S \left(1 + \frac{\gamma_{238}}{\gamma_{235}} \delta_{238} \right)} \quad (3-3)$$

where K_3 is an overall proportionality constant.

For a highly thermal flux, equation 3-3 reduces to

$$\left(\frac{P}{A} \right)_\phi = K_3 \left(\frac{M}{S} \right)_\phi \quad (3-3a)$$

The subscript ϕ is used to designate parameters referring to or obtained from the thermal irradiations.

The thermal neutron reaction rates can be calculated from accurately known thermal cross sections. Thus,

$$\left(\frac{P}{A} \right)_\phi = \left(\frac{\bar{\Sigma}_{235U}^{fiss}}{\bar{\Sigma}_{abs}^B} \right)_\phi \quad (3-4)$$

where

$\bar{\Sigma}_{235U}^{fiss}$ = average macroscopic thermal cross section for ^{235}U fission in fuel sample,
 $\bar{\Sigma}_{abs}^B$ = average macroscopic thermal cross section of B in LBP samples.

Combining equations 3-3a and 3-4, we obtain

$$K_3 = \left(\frac{\bar{\Sigma}_{235U}^{fiss}}{\bar{\Sigma}_{abs}^B} \right)_\phi \left(\frac{S}{M} \right)_\phi \quad (3-5)$$

Thus, the constant K_3 could be accurately evaluated from molybdenum-99 and sodium-24 activities resulting from the irradiation of small, infinitely dilute samples of fuel and LBP in a highly thermal neutron flux (such as that in the graphite thermal column of the research reactor at Virginia Polytechnic Institute and State University in Blacksburg, Virginia). However, in the

current task, the molybdenum-99 relative saturated activity is measured without chemical separation, and we experienced difficulties in applying the large decay corrections required when UO_2 was irradiated at another site and then transported back to B&W for molybdenum-99 counting.

To circumvent these difficulties, an alternate approach was used in which Dy-Al foil irradiations at the thermal facility were used in place of UO_2 . This approach is made possible by the introduction of previously measured activation ratios as reported in reference 9. For these earlier measurements the relative saturated activity for molybdenum-99 was determined by counting molybdenum that had been chemically separated from other fission products and from uranium. Accurate decay correction was not a problem with the purified samples.^{9,18}

If we adopt the following additional nomenclature,

M = relative saturated activity of ^{99}Mo in an irradiated fuel sample as determined without chemical separation,

M' = relative saturated activity of ^{99}Mo in an irradiated fuel sample as determined by chemical separation,

K = foil factor accounting for variations in dysprosium content of the foils,

X = saturated activity in Dy-Al foil,

μ = data taken in the CX-10 in a position designated⁹ as position 3, core VI-A, loading 6 or an equivalent position in the current lattice,

then

$$\left(\frac{S}{M}\right)_{\phi} \approx \frac{(M'/KX)_{\mu} (S/KX)_{\phi}}{(M/KX)_{\mu} (M'/KX)_{\phi}} \quad (3-6)$$

In addition to the previously measured activation ratios reported in reference 9, one additional ratio measurement in the critical facility is required. This ratio, designated $(M/KX)_{\mu}$ in equation 3-6, was taken in position W1 of core IV-K (see section 4), which is essentially equivalent to position 3 of core VI-A. Since data from reference 9 show that the ratio of molybdenum-99 activity to Dy-Al foil activity varied by less than 3% over a wide range of critical experiment loadings, we are confident that the slight difference in core loadings introduces no error exceeding 0.5% into equation 3-6.

Combining equations 3-3, 3-5, and 3-6 we obtain

$$\left(\frac{F}{A}\right)_R = \left[\frac{1 + \delta_{238}}{\theta \left(1 + \frac{Y_{238}}{Y_{235}} \delta_{238} \right)} \right]_R \left(\frac{\bar{\epsilon}_{fiss}^{235U}}{\bar{\epsilon}_{abs}^B} \right)_\phi \frac{(M'/KX)_\mu (S/KX)_\phi}{(M/KX)_\mu (M'/KX)_\phi} \left(\frac{M}{S} \right)_R \quad (3-7)$$

The quantities $(M/KX)_\mu$, $(M/S)_R$, and $(S/KX)_\phi$ will be measured experimentally in the current program. The terms $(M'/KX)_\mu$ and $(M'/KX)_\phi$ were measured during a previous program. All other terms will be evaluated theoretically or obtained from the literature.

3.4. Measurements

3.4.1. Lattice Irradiations

The lattice irradiations were performed in the central element of core XIII by using one special fuel rod and two special poison pins. Figure 3-4 shows the location of the 16 LBP pins and the special test fuel pins. The first and second series of measurements used thin and thick-walled LBP pins, respectively. Within each series of measurements, sample fuel pellets and test LBP sections were irradiated in two different configurations, as indicated in Figure 3-4 by Cases I and II.

During these irradiations, the sample fuel pellet and the sample LBP section were centered 78.7 cm above the reference plane. Axial power variations were eliminated by adjusting the moderator boron concentration and the auxiliary control rod position so that the critical moderator height was always 145.0 cm above the reference plane. The total core power was normalized with two 0.25-inch-diameter gold foils, which were located 75 cm above the reference plane on the cladding of the fuel pins in positions N8E15 and N8W15. All irradiations were for 20 minutes at about 1 kW.

Excess reactivity was controlled by dissolving boric acid (H_3BO_3) in the demineralized water moderator. The boron concentration in parts per million (ppm) is defined as the grams of natural boron per million cm^3 of moderator at 25C. The boron concentration is determined by titration against a standard KOH solution and has an absolute standard deviation of ± 3 ppm. The boron concentrations used during the thin- and thick-walled LBP pin irradiations were 1249 and 1278 ppm, respectively.

After all poison pins were removed from the core, a fuel pellet was irradiated in position S5E1 with a calibrated Dy-Al foil above and below the pellet. These foils, which contained about 5 wt % dysprosium and were 0.007 inch thick and 0.406 inch in diameter, were separated from the fuel pellet by aluminum foils 0.0005 inch thick. The location chosen for this irradiation was essentially equivalent to position 3 in core VI-A, loading 6.⁹

The radial power distribution through one-eighth of the central element was measured with the thick-walled poison pins in place. The relative pin powers were determined by counting collimated fission product decay gamma from activated fuel rods with an NaI scintillation counting system. The system was biased to count gamma rays of energies greater than 200 keV. Figure 3-5 shows the location of the fuel rods that were gamma scanned. The collimator was a slot, 0.5 inch wide by 1 inch long, in a 2-inch lead shield, which was placed between the fuel rod and the detector so that only the gammas from a 0.5-inch segment of the rod were counted. The detector was surrounded by 2 inches of lead, and other portions of the fuel rod were shielded from the detector by another 2 inches of lead.

To perform activations at a constant moderator height, the boron concentration was adjusted to make the assembly supercritical and to provide a reasonable exponential period at a moderator level of 145.0 ± 0.1 cm. The integrated exposures were typically 1 kW-min. The activated fuel rods were then counted after a 45-minute decay time. The rods were counted at an elevation of 78.7 cm above the reference plane and were rotated while being counted to provide data that are independent of fuel rod orientation. Counting time varied from 53 to 156 seconds, and the total counts from each rod ranged from approximately 30,000 to 40,000. The background activity was kept low by loading fuel rods with very low integrated power histories in the positions to be measured.

Decay corrections were obtained from a "master" fuel rod, which was irradiated simultaneously with the rods to be counted and was counted on a second counting system. The electronics of the second system was identical to that of the first counting system. Counts were taken on the two counting systems simultaneously, and during the acquisition of data from a given irradiation, the master fuel rod was never moved. A standard fuel rod was recounted at frequent intervals to check the stability of the two counting systems. As shown in Figure 3-5, each of the relative fission densities has a standard error of $\pm 0.5\%$.

3.4.2. Sample Processing

Soon after shutdown, the two removable LBP sections were removed, weighed, and dissolved in 250 ml of demineralized water in polyethylene bottles. The pre-weighed sample fuel pellet was also removed and dissolved in 250 ml of warm concentrated nitric acid in a polyethylene bottle.

3.4.3. Sample Counting

Soon after being dissolved, the LBP samples were gamma-counted on Ge-Li detector-4096 multichannel analyzer system. The time from reactor shutdown to the start of counting varied from 26 to 390 minutes. The live counting time was 10^4 seconds for samples from thick-walled pins. Both the 2.75- and 1.37-MeV sodium-24 gamma peaks were counted.

The fuel sample was also gamma-counted in the same geometry and on the same counting system. The time from reactor shutdown to the start of counting varied 1230 to 1555 minutes, and the live counting time was 10^3 seconds. The 140.5 keV gamma peak from the molybdenum-99 decay was the peak of interest.

The Dy-Al foils were washed to remove any surface contamination and were then counted on the bottom shelf of three end-window, gas-flow proportional counters.

3.4.4. Thermal Irradiation

Samples of simulated LBP material were prepared by dissolving a few grams of NaBF_4 in water. Small quantities of this solution, each containing about 3 mg of NaBF_4 , were deposited onto 0.49-inch-diameter circles of filter paper and dried under a heat lamp. The filter circles, each in a 0.5-inch-diameter aluminum box, were carefully covered with 0.0005-inch-thick aluminum foil. Similarly, one calibrated Dy-Al foil was placed in an aluminum box and covered with aluminum. These filter circles ensured a uniform deposit and had a negligible effect on the thermal neutron flux. The calculated thermal self-shielding and flux depression for the Dy-Al foil and the LBP samples were 0.4 and 1.0%, respectively.

The thermal irradiation was made in the 5- by 4- by 5-foot graphite thermal column of the research reactor at Virginia Polytechnic Institute and State University in Blacksburg, Virginia. The Dy-Al foil and LBP samples (all in identical boxes) were mounted on a wheel that rotated in a relatively constant thermal flux. The wheel assembly consisted of a 4- by 4- by 12-inch graphite stringer recessed at one end for a 3.5-inch-diameter Lucite wheel. A shaft

connected the wheel to a 1-rpm, geared electrical drive motor, which was recessed into the other end of the graphite stringer. The 0.375-inch-thick Lucite wheel has eight machined depressions to accommodate the aluminum sample boxes. A second 0.375-inch-thick Lucite disc covered the boxes. The graphite stringer containing the loaded wheel assembly was positioned along the axis of the graphite thermal column so that the samples and the gamma curtain shielding the reactor core were separated by approximately 32 inches of solid graphite. Approximately 23 inches of graphite backed up the rotating Lucite wheel.

Previous measurements at the 32-inch position have shown the thermal flux to be about $3 \times 10^5 \text{ n/s}^{-1}\text{-cm}^{-2}\text{-W}^{-1}$ and the cadmium ratio of 0.0001-inch thick gold to be about 600.

One 10 kW irradiation was made for a duration of 1 hour. As soon as possible after shutdown, the Lucite wheel containing the samples was removed and transported to the LRC for sample processing. The LBP samples were redissolved in 250 ml of water along with approximately 600 mg of unirradiated NaBF_4 . The resultant solution was then counted in the same geometry and manner as described for the lattice irradiations. The Dy-Al foil was also counted as in the lattice irradiations.

3.4.5. Results

The molybdenum-99 and sodium-24 data from the lattice irradiations were converted to relative saturated activities (Table 3-1 and 3-2). The relative saturated activities resulting from the UO_2 and dysprosium lattice irradiation and from the NaBF_4 and dysprosium thermal irradiation are shown in Tables 3-3 and 3-4.

To evaluate $(F/A)_R$, the following values are used:

$$\frac{Y_{238}}{Y_{235}} = 1.03 \pm 0.03 \quad (\text{ref 9})$$

$$\delta_{238} = 0.07 \pm 0.01 \quad (\text{ref 9})$$

$$\bar{\epsilon}_{fiss}^{235\text{U}} = 0.03127 \pm 0.00006 \text{ cm}^2/\text{g } \text{UO}_2 \quad (\text{ref 10})$$

$$\bar{\epsilon}_{abs}^B = 4.125 \pm 0.024 \text{ cm}^2/\text{g } \text{NaBF}_4$$

$$(S/KX)_\phi = (7.89 \pm 0.03) \times 10^{-2} \quad (\text{Table 3-4})$$

$$(M'/KX)_\phi = 8.32 \pm 0.05 \quad (\text{ref 9})$$

$$(M/KX)_p = (4.93 \pm 0.02) \times 10^{-4} \quad (\text{Table 3-4})$$

$$(M'/KX)_p = 9.77 \pm 0.11 \quad (\text{ref 9})$$

$$\theta = 1.0 \quad *$$

Substituting these values into equation 3-7 yields

$$(F/A)_R = (1.422 \pm 2\%) (M/S)_R. \quad (3-8)$$

Applying equation 3-8 to the values presented in Tables 3-1 and 3-2 gives the final values of fission rate and absorption rate, which are presented in Table 3-5. These final values reflect the relationship between the stated reaction rates at the designated locations within the indicated standard deviations; however, they do not reflect the actual power level at which the facility was operated.

Table 3-1. Core XIII ^{99}Mo and ^{24}Na Activity Data,
Thin-Walled Poison Pins

Run No.	M, 10^2 cts/min-g UO_2		S, 10^4 Cts/min-g NaBF_4		
	Core position		Core position		
	<u>S3E3</u>	<u>S2</u>	<u>S4E4</u>	<u>S2E2</u>	<u>S5E2</u>
1726	3.11	--	2.36	2.40	--
1727	--	3.59	2.16	--	2.44
1728	3.36	--	2.38	2.39	--
1729	--	3.61	2.13	--	2.61
1731	3.33	--	2.19	2.25	--
1732	--	3.39	2.63	--	2.61
Avg	<u>3.27±0.08</u>	<u>3.53±0.07</u>	<u>2.31±0.08</u>	<u>2.35±0.05</u>	<u>2.55±0.06</u>

* The exact value of θ was not calculated.

Table 3-2. Core XIII ^{99}Mo and ^{24}Na Activity Data,
Thick-Walled Poison Pins

Run No.	M, 10^2 cts/min-g UO_2		S, 10^4 cts/min-g NaBF_4		
	Core position		Core position		
	S3E3	S2	S4E4	S2E2	S5E2
1737	--	4.56	--	--	4.78
1738	4.53	--	4.80	4.35	--
1739	--	4.66	4.37	--	4.86
1742	4.45	--	4.40	3.99	--
1743	--	4.67	5.20	--	4.93
1744	4.50	--	4.76	4.24	--
Avg	4.49 ± 0.02	4.63 ± 0.04	4.71 ± 0.15	4.19 ± 0.11	4.86 ± 0.04

Table 3-3. Calibration Ratio Obtained in Lattice Position
Equivalent to Position 3, Core VI-A

M, cts/min-g UO_2	$(3.00 \pm 0.01) \times 10^2$
KX cts/min	$(6.088 \pm 0.012) \times 10^5$
$(M/KX)_\mu$	$(4.93 \pm 0.02) \times 10^{-4}$

Table 3-4. Calibration Ratio Obtained in VPI
Thermal Column Irradiation

S, cts/min-g NaBF_4	$(4.587 \pm 0.010) \times 10^6$
KX, cts/min	$(5.814 \pm 0.015) \times 10^7$
$(S/KX)_\phi$	$(7.89 \pm 0.03) \times 10^{-2}$

Table 3-5. Fission Rate Vs Boron Absorption Rate

Case	F, fissions/s-g UO ₂		A, boron abs/s-g NaBF ₄		
	S3E3 ^(a)	S2	S4E4	S2E2	S5E2
Thin-walled LBP	$(4.65 \pm 0.13) \times 10^{-2}$	$(5.02 \pm 0.12) \times 10^{-2}$	2.31 ± 0.09	2.35 ± 0.06	2.55 ± 0.07
Thick-walled LBP	$(6.38 \pm 0.09) \times 10^{-2}$	$(6.58 \pm 0.11) \times 10^{-2}$	4.71 ± 0.16	4.19 ± 0.12	4.86 ± 0.08

(a) Indicates position.

Figure 3-1. Typical Fuel Rod

Figure 3-2. Poison Sample Pin

Figure 3-3. Core XIII Loading Diagram

Figure 3-4. Central Element Cross Section

Case I

- ⊗ - Inconel Tube
- - LBP Pin
- Ⓢ - Sample LBP Pin
- ⓕ - Sample Fuel Pin

Case II

Figure 3-5. Relative Fission Density in Central Element
With Thick-Walled Poison Pins

- - Inconel Tube
- NaBF₄ Filled Pine

4. TASK 10 - PROMPT INCORE DETECTOR STUDY (M. N. Baldwin, H. D. Warren)

4.1. Introduction

Task 10 was undertaken to obtain experimental data for use in assessing the relative magnitude of the neutron- and gamma-induced signal components from an all-solid, prompt-responding incore detector. To achieve this objective, a number of measurements were taken in three different cores to provide a wide range of neutron spectra and gamma-to-neutron ratios for testing. These measurements included the following:

1. The equilibrium signal from the prompt-responding detector.
2. The background signal produced in the lead section of the detector.
3. The effect on the detector signal when the detector is shielded from thermal neutrons by cadmium.
4. The decay of the detector signal following shutdown of the critical facility.
5. The neutron flux to which the detector is subjected.
6. The gamma dose to which the detector is subjected.
7. The fission density in fuel rods adjacent to the detector.

4.2. Description of Assemblies

4.2.1. Facility and Fuel

The facility and the fuel rods are the same as those used in Task 8 and described in section 2.

4.2.2. Ag-In-Cd Pins

The poison pins used in Task 10 are an alloy of silver, indium, and cadmium. The 0.400-inch-diameter pins have an approximate composition of 80 wt % silver, 15 wt % indium, and 5 wt % cadmium. The pins are long enough to span the full core height and are clad in type 321 stainless steel tubes, 0.438-inch OD by 0.016-inch wall. The stainless steel tubes housing poison pins are sealed at the bottom by 0.125-inch-thick stainless steel end plugs (welded in place) and at the top by a removable cork plug. Table 4-1 summarizes the physical properties of the poison pins.

4.2.3. Core Description

Top and bottom plates align the fuel rods in the core tank. The top and bottom egg-crate grid plates are slotted aluminum strips 1 inch wide that are interlocked to form a square matrix. The 0.160-inch-thick strips are spaced on centers of 0.644 ± 0.002 inch.

The fuel rods are supported on a 2-inch-thick aluminum base plate, which is raised about 1 inch above the bottom of the 5-foot-diameter tank. The intervening space is filled with moderator. Moderator levels are measured from a reference plane at the bottom of the active fuel. The fuel rods and perturbing pins are uniformly spaced at intervals of the lattice pitch.

Each of the 8-inch-wide boral safety blades is thin enough to pass between rows of fuel rods, so that uniform lattice spacing can be maintained. During measurements, the safety blades are held in a cocked position to minimize their contribution to core perturbations. Criticality is achieved by raising the level of the moderator.

Three different cores were loaded for the Task 10 measurements. Figures 4-1 and 4-2 are loading diagrams of these cores. Each core contained a 0.75-inch-OD by 0.028-inch wall aluminum (type 5052) tube at the center position; the tube was sealed at the bottom to exclude moderator and was open at the top to allow the introduction of both bare and cadmium-covered foils, wires, an ionization chamber, and incore detectors. The three cores provide a wide range of neutron spectra and gamma-to-neutron ratios with which to test the prompt in-core detector.

4.2.4. Moderator Boron

The large excess reactivity of core IV-K was controlled by dissolving boric acid (H_3BO_3) in the demineralized water moderator. The boron concentration in parts per million (ppm) is defined as the grams of natural boron per million cm^3 of moderator at 25C. The boron concentration was determined by titration against a standard KOH solution. The measurements have an absolute standard deviation of ± 3 ppm.

The measured moderator concentration of core IV-K was 1469 ppm. This concentration produces a k_{eff} of 1.0000 when the height of the moderator is 145.0 cm, all safety blades are fully withdrawn, and the auxiliary reactivity control rods (section 4.2.5) are at an intermediate position. The moderator boron

concentration of cores X-L and X-K was intended to be zero; however, a small residue of boric acid that remained in the core and dump tanks after the moderator was removed resulted in an actual measured concentration of 4 ppm for cores X-L and X-K.

4.2.5. Auxiliary Reactivity Control

The nature of the experimental measurements dictates that all data be taken with the safety blades cocked in their fully withdrawn position and with the moderator height as nearly constant as possible. Since there are variations in the reactivity worth of the foils, cadmium covers, radiation detectors, etc. that must be placed in the core for measurements, and since some measurements must be made with the facility at constant power while others must be made with the power rising, some small auxiliary control is therefore required.

To provide this control in core IV-K, two fuel rods in the southwest quadrant were replaced with two Ag-In-Cd pins connected to a drive system. The total reactivity worth of these pins from the full-in to the full-out position was about 4 cents. Prior measurements have shown that the power profile for the area in which the data were taken is not affected by the poison pins. By employing this two-pin control plus adjustments of up to 3 ppm in the moderator boron concentration, all core IV-K measurements could be made at a moderator height of 145.0 cm.

Unfortunately, this method of control was not practical for cores X-L and X-K since these cores are so much smaller that the poison control pins would be too near the point of measurement. Additionally, at moderator boron concentrations near zero, huge quantities of diluting water would be required to reduce the boron concentration.

To maintain the moderator level of cores X-L and X-K at a reasonably constant height during measurements, the number of fuel rods making up the cores was varied as shown in Figure 4-2. By varying the loading of core X-L by up to two fuel rods, all measurements could be made at a moderator height between 145.24 and 146.06 cm. By varying the loading of core X-K by up to 10 fuel rods, all measurements could be made at a moderator height between 144.06 and 146.55 cm.

4.3. Measurements

4.3.1. Prompt-Responding Detector

The prompt-responding detector* (Figure 4-3) utilizes an 0.0506 ± 0.0002 -inch-OD ytterbium emitter ($\rho = 6.98 \text{ g/cm}^3$), which produces current by converting capture gammas into photoelectric and compton electrons with sufficient energy to escape the emitter.

The density of the MgO insulator exceeded 98% of theoretical. The detector is approximately 9 feet long and has an electrical resistance of $>10^{13}$ ohms between the inner conductor and the sheath. The capacitance between these same conductors is 1.2 nf.

4.3.2. Background Detector

Small unwanted currents are produced by a variety of atomic and nuclear reactions in the lead section of the detector. These currents are measured with a background detector that is identical in construction to the lead section of the prompt-responding detector. There is no emitter section in the background detector.

4.3.3. Signal Measurements

The detector signal current was measured by a Cary Model-401 vibrating reed electrometer (Figure 4-4). A Hewlett-Packard Model-3460B digital voltmeter was used as a readout device to gain precision in the measurements. A 50-foot, mineral-insulated cable connected the detectors positioned in the core to the electrometer preamplifier in the control room. The mineral-insulated cable is insensitive to both electromagnetic noise and temperature fluctuations. The electrical resistance of the cable was $>10^{13}$ ohms, and the total capacitance was approximately 3.3 nf (70 pf/ft).

The high-resistance leak method was used to measure current; this is basically the measurement of the voltage drop across a precision resistor. The current output of the detector is determined by

$$I = E_r / R_1 \quad (4-1)$$

- - - - -
* This patented detector was fabricated at B&W's Lynchburg Research Center by E. L. Glass and F. L. Mason, under the direction of Dr. H. D. Warren.

where

E_r = voltage developed across R_1 ,

R_1 = resistance of the particular precision resistor in use
within the Cary electrometer.

The Cary electrometer has three precision resistors with approximate values of 10^8 , 10^{10} , and 10^{12} ohms. For the present measurements, the $\sim 10^{12}$ ohm resistor (calibrated against a Keithley Model 515-megohm bridge having a quoted accuracy of 0.5%) was used exclusively. Since the electrometer's amplifier gain is approximately 1000, the effective input resistance to the electrometer is about 10^9 ohms. This is at least a factor of 10^4 below the internal resistance of the detectors and connecting cable; thus, essentially all of the current produced by the detector passes into the electrometer and is measured. Measurements with the Cary electrometer are accurate to about 1% for currents larger than 5×10^{-13} amperes.

Both bare and cadmium-covered measurements of the detector signal and its background were taken. Values following 30-minute irradiations at constant power are given in columns 3 through 6 of Table 4-4.

The bare detector measurements were taken with the detector positioned in the empty 0.75-inch-diameter center tube so that the center of the emitter was 79.4 cm above the reference plane. Companion background measurements were taken with the background lead section of the detector terminating 101.7 cm above the reference plane.

During the cadmium-covered measurements, the emitter section of the detector was enclosed in a 20-inch-long by 0.260-inch-OD by 0.30-inch-wall cadmium tube that was pinched off at the top and bottom ends. Again the detector was positioned so that the center of its emitter was 79.4 cm above the reference plane. Companion cadmium-covered background measurements were taken with the background detector lead section terminating 101.7 cm above the reference plane. Since the position of the cadmium tube was duplicated in both measurements, in the latter measurement most of the cadmium tube was actually below the end of the background detector.

4.3.4. Delayed Signal Component

The response of a detector to a rapid power transient cannot be fully evaluated in a low-power critical assembly. Since a very sensitive instrument with an inherently long time constant must be used to measure the very small detector

signal, delayed signal components with short time constants are obscured. However, the measurements described in this section may be used to evaluate the magnitude of delayed signal components having a long time constant relative to that of the measuring system.

Detector signal decay was recorded following shutdown of cores IV-K, X-K and X-L. For these measurements, the detector was positioned in the cores as described in section 4.3.3. Shutdown was accomplished by dropping the safety blades. Since the detector is gamma-sensitive, the moderator was maintained at the normal operating height until all data were recorded to prevent changing the gamma attenuation characteristics of the core. The total rod worth for core IV-K was approximately \$3.60. The total rod worth for cores X-K and X-L was about \$15. The effective time constant (RC) of the detector and measuring instrumentation was 15.9 seconds. The signal decay data are presented in Table 4-2 and in Figures 4-5, 4-6, and 4-7.

4.3.5. Neutron Flux Measurements

Bare and cadmium-covered gold wires and foils were used to measure the 2200 meter/second neutron flux (ϕ_0). Since thermal neutrons have a continuous distribution of energies, ϕ_0 is a somewhat artificial concept. Nevertheless, flux is often quoted in terms of ϕ_0 since it can be easily measured by a 1/v detector.^{19,20} In general, the magnitude of ϕ_0 is less than the actual thermal flux, which is defined as

$$\phi_{th} = \int_0^{0.5\text{eV}} \phi(E) dE,$$

but no error is introduced in using ϕ_0 to compute reaction rates if the material involved has a 1/v cross section over the thermal energy range and if the cross section used is for 0.0252 eV neutrons. Thus,

$$R = \Sigma_0 \phi_0$$

where

R = reaction rate, reactions/cm³-s,

Σ_0 = reaction cross section for a 1/v absorber to 0.0252 eV neutrons, cm⁻¹,

ϕ_0 = 2200 meter/second neutron flux, n/cm²-s.

The principal advantage gained by using ϕ_0 is that the thermal neutron distribution need not be known.

The standard foil technique normally used at the Lynchburg Research Center for measuring ϕ_0 relates the saturated count rate induced by thermal neutron capture in a standard 0.259-inch by 0.005-inch-thick gold foil to the absolute 2200 meter/second neutron flux as follows:

$$\phi_0 = (9.60 \pm 0.34)A_s$$

where A_s is the saturated count rate induced in the standard gold foil by thermal neutron capture (counts/minute when measured on the top shelf of three end-window, gas-flow proportional counters). By intercalibration, a similar expression was obtained for the gold wire used in the present experiments.

The bare-wire measurements were taken by irradiating 18-inch-long gold wire. To maintain the wire rigid and straight during irradiation, it was placed inside an Inconel tube (0.059-inch-OD by 0.011-inch wall), which was centered in the 0.75-inch tube that occupied the center of each core. Following irradiation, three selected 1-inch segments of each wire were cut out and counted in each of three end-window, gas-flow proportional counters.

The cadmium-covered wire measurements were taken in an identical manner except that 2-inch-long segments of 0.160-inch-OD by 0.020-inch-wall cadmium tubing were taped on the outside of the Inconel tubing at the three elevations of interest.

Random uncertainties in determining ϕ_0 are about 0.5%. In addition, a 3.5% systematic error exists because of uncertainty in the thermal flux value where the standard gold foils were originally calibrated.

4.3.6. Power Profile Measurements

The relative power distribution along the length of two fuel rods adjacent to the detector position of cores X-K and IV-K was measured by counting collimated fission product gammas from activated fuel rods. Gamma photons of less than 350 keV energy were discriminated out. The collimator consisted of a 0.5-inch-wide by 1-inch-long slot in a 2.5-inch-thick lead shield placed between the fuel rod and the detector so that only the gammas from a 0.5-inch segment of the rod were counted. The detector was surrounded by at least 4 inches of lead,

and other portions of the fuel rod were shielded from the detector by a least another 5 inches of lead.

The fuel rods scanned were taken from core positions W1 (one pin pitch west of center) and NW1 (one pin pitch west by one pin pitch north of center), following a 1 kW-min exposure, and were rotated while being counted to provide data that were independent of the orientation of the rod. All activations were performed at as close to the same moderator height as possible within the limitations detailed in section 4.2.5. The background activity was kept low by loading fuel rods with very low power histories in the positions to be studied.

Decay corrections were obtained from a "master" fuel rod, which was irradiated in the east imaginary element simultaneously with the rods to be scanned and then counted in a second counting system. The electronics of the second system was identical to that of the first. Counts were taken on the two systems simultaneously, and the master fuel rod was never moved during the acquisition of data on a given run. A standard fuel rod was recounted frequently to check the stability of the two systems.

Relative power profile data for the two fuel rods adjacent to the detector position of cores X-K and IV-K are given in Table 4-3 and plotted in Figures 4-8 and 4-9. The standard deviation of these data is about 1%.

4.3.7. Fission Density Determination

The power distribution measurements reported in section 4.3.6 are relative. To relate them to incore detector signal measurements, they must be normalized to some absolute determination of fission density. A determination based on the molybdenum-99 content of an irradiated fuel sample was made at the LRC in 1967 in a critical assembly lattice almost identical to the one now being studied. A relationship established between Dy-Al foil activation and fission density during the 1967 measurements can be used to determine the appropriate normalizing factor; i.e.,

$$F = (9.6 \pm 0.5)(K)(X)$$

where

K = foil factor accounting for variations in the dysprosium content of foils,

X = saturated count rate induced in Dy-Al foils (counts/minute measured on the bottom shelf of three end-window, gas-flow proportional counters),

F = fission density (fissions/g 2.46% enriched UO_2) within the sample fuel pellet between Dy-Al foils.

The fuel pellets and Dy-Al foils were loaded inside a fuel rod, as shown in Figure 4-10, and were irradiated in cores IV-K and X-K. The sample pellet was centered 78.4 cm above the reference plane.

4.3.8. Dose Rate Measurements

A Bendix Model CDV-746, 0 to 600 R self-reading pocket ionization dosimeter was used for both bare and cadmium-covered dose rate measurements in the 0.75-inch center tube of each core. The dosimeter has a sensitive length of about 0.5 inch and a quoted accuracy of $\pm 10\%$ of true dose from radium or cobalt-60 gamma rays. The dosimeter was zeroed and positioned in the core immediately before startup, irradiated at a suitable constant power level for 10 minutes, and removed from the core immediately after shutdown. A power level was selected for all dosimeter irradiations, which gave total dose readings between 237 and 265 R. Identical irradiations showed that the readings were reproducible to within 2%. Other auxiliary irradiations showed that the dose recorded by the dosimeter before and after the power irradiation was negligible.

4.3.9. Ytterbium-Cadmium Ratio Measurements

Of the seven stable isotopes of natural ytterbium, ytterbium-174 contributes most of the neutron sensitivity of an ytterbium incore detector. The macroscopic neutron capture cross section of this isotope accounts for more than half of the total macroscopic cross section of the natural element. After ytterbium-174 captures a neutron, the residual nucleus, ytterbium-175 beta decays with a 4.19-day half-life and a maximum decay energy of 467 keV. These betas can be counted with conventional counters without interference from other ytterbium isotopes. No other ytterbium isotope has a half-life greater than 1.9 hour.

The cadmium ratio of ytterbium-174 was determined by irradiating and beta-counting natural ytterbium foils 0.259-inch in diameter by 0.0014 inch thick. Both bare and cadmium-covered foils were activated in core X-K inside the 0.75-inch center tube. The foils were counted in the three end-window proportional counters after a wait time of 20.0 hours. The cadmium ratio is listed in the last column of Table 4-4.

Table 4-1. Properties of Ag-In-Cd Poison Pins

<u>Item</u>	<u>Value</u>
Length, in.	62.03 $\pm$ 0.00
Diameter, in.	0.400 $\pm$ 0.000
Weight, g	1296 $\pm$ 5
Analysis, wt %	
Silver	79.68
Indium	15.09
Cadmium	5.2
Copper	0.05
Zinc	0.016
Lead, nickel, tin, iron, aluminum, bismuth	<0.001

Table 4-2. Signal Decay Following Shutdown (RC = 15.9 s)

Time, s	Core IV-K		Core IV-K		Core X-L		Core X-L		Core X-K		Core X-K	
	cd cov run 1799 (31 min oper)	bare run 1783 (31 min oper)	cd cov run 1828 (42 min oper)	bare run 1826 (36 min oper)	cd cov run 1862 (38 min oper)	bare run 1864 (45 min oper)	cd cov run 1862 (38 min oper)	bare run 1864 (45 min oper)	cd cov run 1862 (38 min oper)	bare run 1864 (45 min oper)	cd cov run 1862 (38 min oper)	bare run 1864 (45 min oper)
0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
5	0.877	—	0.888	0.862	0.903	0.867	0.903	0.867	0.903	0.867	0.903	0.867
10	0.756	0.707	0.769	0.740	0.765	0.700	0.765	0.700	0.765	0.700	0.765	0.700
15	0.636	0.560	0.639	0.613	0.648	0.581	0.648	0.581	0.648	0.581	0.648	0.581
20	0.536	0.487	0.536	0.527	0.551	0.464	0.551	0.464	0.551	0.464	0.551	0.464
25	0.455	0.384	0.453	0.438	0.472	0.375	0.472	0.375	0.472	0.375	0.472	0.375
30	0.389	0.313	0.384	0.377	0.405	0.314	0.405	0.314	0.405	0.314	0.405	0.314
35	0.342	0.253	0.336	0.318	0.352	0.253	0.352	0.253	0.352	0.253	0.352	0.253
40	0.292	—	0.290	0.271	0.302	0.207	0.302	0.207	0.302	0.207	0.302	0.207
45	0.262	0.167	0.253	0.240	0.274	0.175	0.274	0.175	0.274	0.175	0.274	0.175
50	0.234	0.144	0.249	0.207	0.246	0.147	0.246	0.147	0.246	0.147	0.246	0.147
55	0.209	0.122	0.203	0.182	0.221	0.123	0.221	0.123	0.221	0.123	0.221	0.123
60	0.190	0.105	0.183	0.165	0.203	0.107	0.203	0.107	0.203	0.107	0.203	0.107
65	0.176	0.0893	0.166	0.148	0.187	0.0940	0.187	0.0940	0.187	0.0940	0.187	0.0940
70	0.160	0.0802	0.152	0.137	0.174	0.0814	0.174	0.0814	0.174	0.0814	0.174	0.0814
75	0.150	0.0700	0.144	0.126	0.161	0.0736	0.161	0.0736	0.161	0.0736	0.161	0.0736
80	0.143	0.0627	0.135	0.116	0.153	0.0658	0.153	0.0658	0.153	0.0658	0.153	0.0658
85	0.136	0.0573	0.127	0.110	0.146	0.0605	0.146	0.0605	0.146	0.0605	0.146	0.0605
90	0.130	0.0513	0.121	0.103	0.140	0.0557	0.140	0.0557	0.140	0.0557	0.140	0.0557
95	0.123	0.0480	0.115	0.0978	0.134	0.0518	0.134	0.0518	0.134	0.0518	0.134	0.0518
100	0.117	0.0433	0.111	0.0929	0.130	0.0490	0.130	0.0490	0.130	0.0490	0.130	0.0490
105	0.114	0.0431	0.107	0.0896	0.125	0.0461	0.125	0.0461	0.125	0.0461	0.125	0.0461
110	0.111	0.0407	0.104	0.0874	0.121	0.0444	0.121	0.0444	0.121	0.0444	0.121	0.0444
115	0.107	0.0394	0.101	0.0843	0.118	0.0432	0.118	0.0432	0.118	0.0432	0.118	0.0432
120	0.105	0.0378	0.0994	0.0820	0.116	0.0413	0.116	0.0413	0.116	0.0413	0.116	0.0413
125	0.103	0.0364	0.0965	0.0800	0.113	0.0407	0.113	0.0407	0.113	0.0407	0.113	0.0407
130	0.0980	0.0364	0.0948	0.0777	0.111	0.0401	0.111	0.0401	0.111	0.0401	0.111	0.0401
135	0.0957	0.0324	0.0931	0.0763	0.109	0.0395	0.109	0.0395	0.109	0.0395	0.109	0.0395
140	0.0925	0.0313	0.0913	0.0749	0.108	0.0395	0.108	0.0395	0.108	0.0395	0.108	0.0395
145	0.0925	0.0329	0.0903	0.0736	0.106	0.0391	0.106	0.0391	0.106	0.0391	0.106	0.0391
150	0.0925	0.0320	0.0886	0.0724	0.104	0.0391	0.104	0.0391	0.104	0.0391	0.104	0.0391
160	0.0828	0.0310	0.0830	0.0683	0.0948	0.0387	0.0948	0.0387	0.0948	0.0387	0.0948	0.0387
170	0.0724	0.0302	0.0762	0.0603	0.0853	0.0378	0.0853	0.0378	0.0853	0.0378	0.0853	0.0378
180	0.0708	0.0302	0.0707	0.0558	0.0782	0.0381	0.0782	0.0381	0.0782	0.0381	0.0782	0.0381
190	0.0592	0.0302	0.0631	0.0533	0.0734	0.0380	0.0734	0.0380	0.0734	0.0380	0.0734	0.0380
200	0.0592	0.0289	0.0614	0.0515	0.0677	0.0366	0.0677	0.0366	0.0677	0.0366	0.0677	0.0366
210	0.0547	0.0294	0.0579	0.0480	0.0641	0.0380	0.0641	0.0380	0.0641	0.0380	0.0641	0.0380
220	0.0514	0.0267	0.0558	0.0478	0.0619	0.0364	0.0619	0.0364	0.0619	0.0364	0.0619	0.0364
230	0.0488	0.0220	0.0543	0.0449	0.0575	0.0354	0.0575	0.0354	0.0575	0.0354	0.0575	0.0354
240	0.0482	0.0220	0.0541	0.0431	0.0582	0.0343	0.0582	0.0343	0.0582	0.0343	0.0582	0.0343
250	0.0443	0.0260	0.0506	0.0412	0.0548	0.0333	0.0548	0.0333	0.0548	0.0333	0.0548	0.0333
260	0.0446	0.0267	0.0488	0.0400	0.0531	0.0337	0.0531	0.0337	0.0531	0.0337	0.0531	0.0337
270	0.0424	0.0238	0.0478	0.0381	0.0503	0.0316	0.0503	0.0316	0.0503	0.0316	0.0503	0.0316
280	0.0414	0.0248	0.0465	0.0386	0.0481	0.0315	0.0481	0.0315	0.0481	0.0315	0.0481	0.0315
290	0.0378	0.0176	0.0448	0.0369	0.0470	0.0313	0.0470	0.0313	0.0470	0.0313	0.0470	0.0313
300	0.0365	0.0184	0.0435	0.0363	0.0450	0.0294	0.0450	0.0294	0.0450	0.0294	0.0450	0.0294
310	0.0356	0.0198	0.0428	0.0353	0.0464	0.0286	0.0464	0.0286	0.0464	0.0286	0.0464	0.0286
320	0.0356	0.0170	0.0420	0.0340	—	0.0290	—	0.0290	—	0.0290	—	0.0290
330	0.0336	—	0.0402	0.0330	0.0437	0.0288	0.0437	0.0288	0.0437	0.0288	0.0437	0.0288
340	0.0349	0.0187	0.0405	0.0322	0.0416	0.0272	0.0416	0.0272	0.0416	0.0272	0.0416	0.0272
350	0.0291	0.0156	0.0397	0.0318	0.0386	0.0265	0.0386	0.0265	0.0386	0.0265	0.0386	0.0265
360	0.0307	0.0160	0.0382	0.0306	0.0403	0.0245	0.0403	0.0245	0.0403	0.0245	0.0403	0.0245
370	0.0310	0.0167	0.0362	0.0302	0.0396	0.0247	0.0396	0.0247	0.0396	0.0247	0.0396	0.0247
380	0.0285	0.0200	0.0367	0.0287	0.0379	0.0241	0.0379	0.0241	0.0379	0.0241	0.0379	0.0241
390	0.0268	0.0144	0.0332	0.0269	0.0352	0.0216	0.0352	0.0216	0.0352	0.0216	0.0352	0.0216
400	0.0246	0.0162	0.0312	0.0236	0.0311	0.0197	0.0311	0.0197	0.0311	0.0197	0.0311	0.0197
410	0.0223	0.0162	0.0287	0.0242	0.0257	0.0185	0.0257	0.0185	0.0257	0.0185	0.0257	0.0185
420	0.0194	0.0140	0.0257	0.0207	0.0244	0.0184	0.0244	0.0184	0.0244	0.0184	0.0244	0.0184
430	0.0178	0.0164	0.0236	0.0185	0.0237	0.0162	0.0237	0.0162	0.0237	0.0162	0.0237	0.0162
440	0.0181	0.0118	0.0216	0.0185	0.0213	0.0148	0.0213	0.0148	0.0213	0.0148	0.0213	0.0148
450	0.0133	0.0107	0.0211	0.0178	0.0193	0.0142	0.0193	0.0142	0.0193	0.0142	0.0193	0.0142

Table 4-3. Results of Fuel Rod Scans

Height above ref plane, cm	Core IV-K		Core X-K	
	Position W1	Position NIW1	Position W1	Position NIW1
57.68	0.599	0.614	0.562	0.578
60.22	.608	.624	.576	.594
62.76	.615	.628	.581	.601
65.30	.618	.634	.586	.606
67.84	.619	.637	.591	.612
70.38	.621	.638	.592	.614
72.92	.620	.636	.594	.617
75.46	.620	.635	.594	.613
78.00	.616	.632	.593	.612
80.54	.613	.631	.587	.605
83.08	.605	.620	.579	.598
85.62	.594	.616	.575	.592
88.16	.588	.606	.561	.585
90.70	.576	.593	.552	.574
93.24	.563	.585	.545	.565
95.78	0.549	0.567	0.525	0.544

Table 4-4. Detector Data Summary

Core	Detector data						Gold wire data			Dosimeter data			Fission rate data			
	Hgt of Yb det emitter ctr., cm	Bare		Cd cov		Au-Cd ratio	Center hgt of bare 1-in. wire seg for mean ϕ_0 , cm	$10^8 \phi_0$, n/cm ² -u	Hgt of dosimeter ctr., cm	Bare dose rate, 10^3 R/h $\pm 1\%$ abs $\pm 2\%$ rel	Cd cov dose rate, 10^3 R/h $\pm 1\%$ abs $\pm 2\%$ rel	Hgt of sample pellet ctr., cm	10^5 fission/g ²³⁵ UO ₂			Cd ratio of Yb foil (²³⁵ Yb)
		Yb det signal after 30 min, 10^{-12} A	Bkgd det signal, 10^{-12} A	Yb det signal after 30 min, 10^{-12} A	Bkgd det signal, 10^{-12} A								Fuel rod WL $\pm 1\%$ abs $\pm 1\%$ rel	Fuel rod NWL $\pm 1\%$ abs $\pm 1\%$ rel		
X-K	79.4	1.790 ± 0.017	-0.059 ± 0.005	0.98 ± 0.10	-0.063 ± 0.010	2.33 ± 0.04	67.8	2.79 ^(a)	67.9	5.72	--	78.4	10.27	10.57	5.91	
							78.3	2.33 ^(a)	77.9	5.68	5.97					
							88.8	2.77 ^(a)	87.9	5.64						
IV-K	79.4	1.499 ± 0.015	-0.049 ± 0.005	1.030 ± 0.010	--	2.05 ± 0.04	67.8	2.18 ^(b)	67.9	5.21	--	78.4	8.07	8.05	--	
							78.3	2.19 ^(b)	77.9	5.27	5.32					
							88.8	2.13 ^(b)	87.9	4.95	--					
X-L	79.4	1.628 ± 0.016	-0.009 ± 0.003	1.308 ± 0.026	-0.026 ± 0.010	1.48 ± 0.05	67.8	0.563 ^(c)	67.9	5.51	--	--	--	--	--	
							78.3	0.571 ^(c)	77.9	5.50	5.57					
							88.8	0.550 ^(c)	87.9	5.14	--					

(a) ± 0.12 abs, ± 0.05 rel.

(b) ± 0.10 abs, ± 0.05 rel.

(c) ± 0.029 abs, ± 0.018 rel.

Figure 4-1. Loading Diagram, Core IV-K

- ⊗ 3/4-Inch OD Aluminum Tube
- Water-Filled Position
- Ag-In-Cd Poison Pin

Figure 4-2. Loading Diagram, Cores X-L and X-K

Core X-L
590-592 Fuel Rods
4 ppm Boron in Moderator

Core X-K
419-429 Fuel Rods
4 ppm Boron in Moderator

- ⊗ 3/4-inch OD Aluminum Tube
- Water-Filled Position
- Supplemental Fuel Rod
- Ag-In-Cd Poison Pin

Figure 4-3. Prompt-Responding Detector(106)

Figure 4-4. Circuit Diagram for Current Measurements

Figure 4-5. Detector Signal Decay Following Shutdown of Core IV-K

Figure 4-6. Detector Signal Decay Following Shutdown of Core X-L

Figure 4-7. Detector Signal Decay Following Shutdown of Core X-K

Figure 4-8. Power Profile — Core IV-K Fuel Rods W1 and N1W1

Figure 4-9. Power Profile - Core X-K Fuel Rods W1 and N1W1

Figure 4-10. Loading Arrangement for Foil Irradiations

5. TASK 11 - 17 BY 17 SUBASSEMBLY MOCKUPS
(M. N. Baldwin)

5.1. Introduction

Task 11 was undertaken to obtain experimental data for use in assessing the reactivity and power perturbation effects of poison pins in 17 by 17 fuel assembly mockups and also to measure the depression of power density in gadolinia-laden fuel pellets.

5.2. Description of Assemblies

5.2.1. Facility and Fuel

The facility and the fuel rods are the same as those used in Task 8 and described in section 2.

5.2.2. Perturbing Pins

Poison and vacant water-filled positions were used to produce lattice heterogeneities for study. The large Pyrex* rods (0.462 inch in diameter) are slightly smaller in diameter than the fuel rods, and the small Pyrex rods are 0.327 inch in diameter. Both contain 12.6 wt % B_2O_3 . They are 188 cm long and have a maxwellian-averaged macroscopic absorption cross section of 3.2 cm^{-1} . The small Pyrex rods are centered in the grid spaces of the top and bottom grid plates by 0.050-inch-thick rubber sleeves, which slip over the poison rods at the grid plate locations.

The Vicor* rods contain about 3 wt % B_2O_3 in pure silica. Their maxwellian-averaged macroscopic cross section (Σ_a) is 0.76 cm^{-1} . The 3-foot-long rods are loaded into type 6061 aluminum tubes, 6 feet long by 0.438-inch OD by 0.035-inch wall. Each tube is sealed at the bottom by a 0.375-inch-thick aluminum plug (welded in place) and at the top by a removable cork plug.

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*Registered trademark, Corning Glass Works.

The Ag-In-Cd poison pins, 0.400 inch in diameter and 62.03 inches long, are composed of 80 wt % Ag, 15 wt % In, and 5 wt % Cd. Their calculated macroscopic thermal cross section is 13.6 cm^{-1} . The alloy pins are clad with 0.438-inch-OD by 0.016-inch-wall type 321 stainless steel. The stainless steel tubes are sealed at the bottom by a 0.125-inch-thick stainless steel end plug (welded in place) and at the top by a removable cork plug.

The B_4C pins are 0.438-inch-OD by 0.035-inch-wall aluminum tubes filled with natural B_4C powder ranging from 30 to 50 mesh. The bottom ends are sealed with welded aluminum plugs, and the tops are sealed with a removable cork plug. The pins contain 156 grams of B_4C , which constitutes a column long enough to span the full core height. The space within the tubes above the B_4C is void and extends about 1 foot above the moderator level. The B_4C is compacted to $2.233 \pm 0.003 \text{ g/inch}$. Pertinent parameters and compositions for the perturbing pins are given in Table 5-1.

5.2.3. Core Description

A loading diagram of core XIV, which is used in Task 11, is shown in Figure 5-1. Imaginary lines divide the center of the core into nine identical elements, 17 lattice pitches square. The grid plates, supporting structure, safety blades, and reference plane for reporting moderator levels are as described in section 2.

5.2.4. Gadolinia-Laden Fuel Pellets

Four batches of sintered, gadolinia-spiked UO_2 fuel pellets were prepared and analyzed by the Ceramics Section of B&W's Lynchburg Research Center (under separate contract) for use in determining the degree of power depression caused by gadolinia. The nominal concentrations of the batches were 0, 0.5, 1.5, and 2.5 wt % Gd_2O_3 . The pellet diameter and density of each batch, along with the results of analyses carried out to determine the actual Gd_2O_3 content, are summarized in Table 5-2. Uncertainties are standard deviations from the mean. The uranium content of the pellets is enriched to 2.53 wt % uranium-235.

The results of 250 X etched photomicrographs and x-ray diffraction measurements carried out at LRC and microprobe measurements performed at Battelle (Columbus) under the separate contract all indicate complete solid solubility.

5.3. Measurements

5.3.1. Reactivity Comparisons

Reactivity comparisons were made between perturbing pins and vacant water-filled positions in the 24 locations of core XIV shown in Figure 5-1. The moderator boron concentration required to give a just-critical condition when the moderator level is 145 cm was used as the measure of reactivity change since it can be readily compared with computer-calculated quantities. The results of these comparisons are presented in Table 5-3. These measurements have an absolute standard deviation of ± 3 ppm.

Radial power distributions were measured through one-eighth of the central 17 by 17 pin pitch array of loadings 4, 5, and 6 by the method described in section 2.2.6. The results of these measurements are presented in Tables 5-4, 5-5, and 5-6. The percentages listed in these power profile tables are standard deviations of the average obtained from two or more measurements.

5.3.2. Power Density Depression Due to Gadolinium

5.3.2.1. Data From Irradiated Pellets and Whole Foils

The fuel pellet irradiations to measure fission density utilized a special fuel rod in core XIV, loading 1, with the sample pellet centered 80.5 cm above the base plate. The first five pellets immediately below the sample pellet (9.52 cm stack length) and the first six pellets immediately above the sample pellet (11.43 cm stack length) were identical in composition to the sample pellet. The remaining pellets in the special fuel rod were identical in composition to those throughout the remainder of the core.

Calibrated Dy-Al foils (about 5 wt % Dy) were positioned on each side of the sample pellet to measure the average thermal flux through the fuel region. These foils, 0.007 inch thick by 0.406 inch in diameter, were separated from the $\text{UO}_2/\text{Gd}_2\text{O}_3$ pellets by aluminum foils 0.0005 inch thick.

Pellets of each gadolinia concentration were irradiated at two locations within the core: grid position E9S9, which is completely surrounded by fuel, and grid position E2S7, which is adjacent to a water-filled position. All irradiations were 10 minutes in duration. For the irradiation of pellets without gadolinia, the assembly was operated at approximately 200 watts steady state. For maximum gadolinia concentrations the assembly was operated at approximately 1 kW.

Power was normalized with the aid of 0.25-inch-diameter gold foils mounted at two reproducible locations on the fuel rod located in grid position N1E30. Following irradiation, the Dy-Al foils were counted in end-window, gas-flow proportional counters to determine their saturated count rate. Each sample pellet was dissolved in nitric acid, diluted to precisely 200 ml with additional nitric acid, and transferred to a plastic bottle for counting. Each sample was counted under identical geometric conditions for t_c seconds.

The activity of the fission product molybdenum-99 was chosen as an accurate measure of the relative fission rate in gadolinia-spiked fuel pellets. Because of its intensity, the 0.1405 MeV photopeak emitted by its daughter $^{99}\text{Tc}^m$ was actually used for the measurements. At least 60 hours were allowed after sample preparation before any counts were taken to allow the technetium-99 to come into transient equilibrium with its parent, molybdenum-99.

The samples were gamma-counted on a Ge(Li) detector-multichannel analyzer system. More specifically, this system comprised (1) a model LGCUS8ED Princeton Gamma-Tech Ge(Li) detector with a nominal active volume of 45 cm³, (2) a model RG-11 Princeton Gamma-Tech preamplifier, (3) a Model TC-211 Tennelec linear amplifier, (4) a Model AEC 5000 Tennelec High Voltage Power Supply, and (5) a Model NS-700 Northern Scientific Pulse Height Analyzer.

The analyzer is equipped with lower and upper level discriminators and with an analog zero level control. The latter control has the effect of shifting the entire spectrum to lower channels. Utilizing these controls along with a very high amplifier gain, a region of interest was established in which the 140.5-keV photopeak of $^{99}\text{Tc}^m$ was centered at channel 181. Channels 163 (139.6-keV) through 200 (141.4 keV) were summed to measure the $^{99}\text{Tc}^m$ activity.

The experimental results of the pellet irradiations are given in Table 5-7. The bottom entry gives the results from a dissolved unirradiated pellet that was used for a background correction. Then, using 65.98 ± 0.10 hours as the half-life¹⁸ for the parent molybdenum-99, the background-corrected counts are decay-adjusted to a common (72.00 h) time (t_w) following irradiation. The adequacy of this adjustment over a two-half-life span is demonstrated with the first pellet listed in Table 5-7.

The relative specific fission rate is obtained by adjusting the background-corrected $^{99}\text{Tc}^m$ count by the gold monitor foil data to account for the

differences in assembly power during the various runs. These values, normalized to unity for the E2S7 position-0% gadolinia case, are given in Table 5-7. Counting statistics contribute about a 2% standard deviation of uncertainty to these measurements, and an estimated 3% standard deviation of uncertainty is contributed by variations in sample preparation and counting geometry. Thus, the standard deviation of uncertainty in the relative specific fission rate is about 3.5%.

The Dy-Al foil data have been similarly adjusted by monitor foil data and normalized to unity for the E2S7 position-0% gadolinia case. These data, which provide the average relative thermal neutron flux through the sample pellet, are easily reproducible to within a standard deviation of 1%.

5.3.2.2. Data From Foil Segments

To ascertain the degree to which the thermal neutron flux is depressed by gadolinia within the fueled portion of the special fuel rod, special segmented Dy-Al foils were prepared from Dy-Al (5 wt % Dy) foil material 0.007 inch thick. The centermost segment was a disc 0.144 inch in diameter, which nested within two annular foils 0.292 and 0.406 inch in diameter to form a single, segmented disc. Two such segmented discs were positioned in the special fuel rod during irradiation in a manner identical to that described in section 5.3.2.1 for the whole foils. Each segment was subsequently counted separately in end-window counters and the data adjusted to saturated count rate.

To correct the data from the segments for differences in size, shape, and dysprosium content, calibration factors were obtained by irradiating the segments on a rotating wheel and comparing their activity with the end-window counters.

The data presented in Table 5.8 are an average from two segmented discs, corrected by the appropriate calibration factor and normalized to unity at the outer annular region.

5.3.2.3. Flux Traverse Data

To ascertain the flux depression caused by the presence of the single special fuel rod containing gadolinia-laden fuel pellets, flux traverse measurements were taken with bare gold foils. The gold foils used were 0.259 inch in diameter by 0.005 inch thick and were taped directly to the west side of the fuel rods (80.2 cm above the bottom of the fueled region) with 0.005-inch-thick Teflon tape and irradiated for 10 minutes at 250 watts. The foils were then

counted in the end-window flow counters, and the resultant data were reduced to saturated count rate and normalized by data from monitor foils located on the fuel rod in position N1E30.

The data in Tables 5-9 and 5-10 compare the neutron flux traverse, as measured by the bare gold foils, with nominal 2.5 and 0% gadolinia concentrations in the fuel of the special fuel rod. The standard deviation of the flux ratio is estimated to be about 1.5%, and the flux perturbation due to the presence of gadolinia does not appear to extend beyond three lattice pitches.

Table 5-1. Physical Properties of Perturbing Pins

Parameter	Vicor	Ag-In-Cd	B ₄ C	Small pyrex	Large pyrex
<u>Perturbing medium</u>					
Material	Vicor glass	Ag-In-Cd	B ₄ C	Pyrex glass	Pyrex glass
Diameter, cm	0.825 ± 0.002	1.016 ± 0.000	0.935 ± 0.001	0.830 ± 0.001	1.170 ± 0.001
Length, cm	183.0 ± 0.3	157.6 ± 0.0	177.5 ± 2.0	188.0 ± 0.1	188.0 ± 0.1
Mass, g	214.5 ± 0.5	1296 ± 5	156.0 ± 0.1	225.4 ± 0.5	453.6 ± 0.6
Analysis, wt %					
B ₂ O ₃	3.035	--	--	12.615 ± 0.007	12.615 ± 0.007
Boron	0.943	--	77.8	3.919	3.919
Silver	--	79.68	--	--	--
Indium	--	15.09	--	--	--
Cadmium	--	5.2	--	--	--
Carbon	--	--	20.8	--	--
Anhydrous B ₂ O ₃	--	--	0.1	--	--
Particle size, % 30 to 50 mesh	--	--	91.2	--	--
<u>Cladding</u>					
Material	6061 Al	304 SS	6061 Al	None	None
Diameter, cm	1.115 ± 0.001	1.120 ± 0.001	1.113 ± 0.001	--	--
Thickness, cm	0.090 ± 0.000	0.046 ± 0.000	0.089 ± 0.001	--	--

Table 5-2. Properties of Special Fuel Pellets

<u>Nominal Gd₂O₃, wt %</u>	<u>Average diameter, inches</u>	<u>Average density, g/cm³</u>	<u>Results of atomic absorption analysis by LRC, wt %</u>
2.5	0.4055 ±0.0002	9.20 ±0.13	2.435 ±0.010
1.5	0.4055 ±0.0003	9.32 ±0.07	1.435 ±0.010
0.5	0.4051 ±0.0003	9.77 ±0.11	0.495 ±0.010
0.0	0.4042 ±0.0002	10.06 ±0.12	-- --

Table 5-3. Core Loadings Studied (All loadings used
4736 fuel rods with 24 positions occupied
by perturbing material and 201; other
vacant positions filled with water.)

<u>Core</u>	<u>Loading</u>	<u>Perturbing material</u>	<u>Moderator B conc producing critical condition when moderator height is 145 cm, ppm</u>
XIV	1	Water	1289
	2	Ag-In-Cd	1165
	3	B ₄ C	1160
	4	Vicor	1246
	5	Small pyrex	1204
	6	Large pyrex	1179

Table 5-4. Midplane Power Profile - Core XIV, Loading 4

		Distance East of Core Center, pin pitches								
		0	1	2	3	4	5	6	7	8
Distance South of Core Center, pin pitches	0	Water			Vicor			Vicor		
	1	1.816 (0.1%)	1.697 (0.2%)							
	2	1.679 (0.2%)	1.686 (0.2%)	1.628 (0.3%)						
	3	Vicor	1.660 (0.5%)	1.651 (0.9%)	Vicor			Vicor		
	4	1.646 (1.2%)	1.648 (0.1%)	1.668 (0.2%)	1.673 (0.5%)	1.638 (0.1%)				
	5	1.647 (0.1%)	1.656 (0.3%)	1.651 (0.5%)	1.671 (1.6%)	1.666 (0.2%)	Vicor			
	6	Vicor	1.651 (0.2%)	1.670 (0.4%)	Vicor	1.686 (0.1%)	1.683 (0.7%)	1.719 (0.6%)		
	7	1.665 (0.3%)	1.671 (0.3%)	1.654 (0.3%)	1.687 (0.1%)	1.699 (0.4%)	1.638 (0.1%)	1.675 (1.3%)	1.702 (0.6%)	
	8	1.681 (0.1%)	1.666 (0.1%)	1.676 (0.3%)	1.670 (0.7%)	1.696 (0.1%)	1.681 (0.4%)	1.682 (0.4%)	1.676 (0.5%)	1.674 (0.8%)

Table 5-5. Midplane Power Profile - Core XIV, Loading 5

		Distance East of Core Center, pin pitches								
		0	1	2	3	4	5	6	7	8
Distance South of Core Center, pin pitches	0	Water			Small Pyrex			Small Pyrex		
	1	1.389 (0.6%)	1.294 (0.1%)							
	2	1.232 (0.7%)	1.259 (1.0%)	1.218 (1.2%)						
	3	Small Pyrex	1.225 (0.5%)	1.228 (0.8%)	Small Pyrex			Small Pyrex		
	4	1.239 (1.1%)	1.243 (0.9%)	1.260 (0.1%)	1.225 (0.5%)	1.229 (0.1%)				
	5	1.238 (0.7%)	1.284 (0.1%)	1.248 (0.9%)	1.248 (0.4%)	1.241 (0.6%)	Small Pyrex			
	6	Small Pyrex	1.252 (1.0%)	1.280 (0.1%)	Small Pyrex	1.309 (0.9%)	1.289 (1.3%)	1.378 (0.6%)		
	7	1.289 (1.3%)	1.327 (0.9%)	1.322 (0.8%)	1.350 (0.7%)	1.353 (1.0%)	1.372 (0.8%)	1.393 (1.0%)	1.455 (0.6%)	
	8	1.407 (0.2%)	1.373 (1.0%)	1.442 (0.5%)	1.403 (0.2%)	1.409 (0.4%)	1.390 (0.3%)	1.453 (0.4%)	1.414 (0.8%)	1.492 (0.8%)

Table 5-6. Midplane Power Profile - Core XIV, Loading 6

		Distance East of Core Center, pin pitches								
		0	1	2	3	4	5	6	7	8
Distance South of Core Center, pin pitches	0	Water			Large Pyrex			Large Pyrex		
	1	1.104 (0.9%)	1.036 (0.3%)							
	2	0.935 (0.3%)	0.989 (0.2%)	0.957 (0.3%)						
	3	Large Pyrex	0.914 (0.4%)	0.918 (0.4%)	Large Pyrex			Large Pyrex		
	4	0.917 (0.2%)	0.983 (0.1%)	0.984 (0.5%)	0.927 (0.3%)	0.954 (0.5%)				
	5	0.956 (0.4%)	0.998 (1.3%)	0.976 (0.6%)	0.932 (0.7%)	0.903 (0.4%)	Large Pyrex			
	6	Large Pyrex	0.967 (0.7%)	0.995 (0.5%)	Large Pyrex	0.964 (0.5%)	1.028 (1.1%)	1.169 (0.7%)		
	7	1.030 (0.7%)	1.086 (0.5%)	1.124 (0.5%)	1.076 (0.3%)	1.128 (0.4%)	1.173 (1.0%)	1.229 (0.1%)	1.286 (0.8%)	
	8	1.186 (0.3%)	1.191 (0.6%)	1.228 (0.4%)	1.214 (0.1%)	1.251 (0.8%)	1.243 (0.8%)	1.291 (0.6%)	1.284 (0.8%)	1.329 (0.4%)

Table 5-7. Summary of Pellet Activation Data

Position	Nominal Gd conc, %	Run	t_c , 10^3 s	Sample pellet wt, g	Counts under $^{99}\text{Tc}^m$ peak			t_w , h	Decay-adj $^{99}\text{Tc}^m$ count	Avg sat ct rate, bare Dy-Al foils, 10^5 cpm	Sat ct rate, bare mon foils, 10^6 cpm	Relative spec flux rate/unit pellet mass	Avg relative neut flux thru sample pellet
					Actual	Norm by t_c and pellet wt	Norm, backgr corr						
E9S9	2.5	1971	7	15.214	5477	5477	4149	72.00	4149	2.020	6.784	0.244	0.179
			7		3161	3161	1833	147.00	4030	--	--	--	--
			7		2214	2214	886	221.33	4253	--	--	--	--
	1.5	1976	7	15.337	4580	4543	3215	75.57	3338	1.618	4.818	0.277	0.202
	0.5	1979	7	15.549	4667	4566	3238	98.03	4257	2.347	4.871	0.349	0.289
	0.0	1984	7	16.160	4799	4518	3190	72.05	3192	1.994	1.402	0.909	0.854
E2S7	2.5	1972	7	14.971	5592	5683	4355	72.00	4355	2.259	6.590	0.264	0.206
	1.5	1975	7	15.304	4633	4606	3278	72.88	3308	1.826	4.842	0.273	0.226
	0.5	1981	7	15.413	6037	5959	4631	75.00	4780	2.835	4.932	0.387	0.345
	0.0	1983	7	15.990	5157	4907	3579	70.15	3510	2.334	1.402	1.000	1.000
Unirr	1.5	--	57	15.304	10,879	1328							

Table 5-8. Data From Foil Segments

		<u>Avg rel thermal neutron flux det by foil segments</u>			
		<u>Grid position E9S9</u>		<u>Grid position E2S7</u>	
<u>Foil segment size, in.</u>	<u>OD</u>	<u>0 wt %</u>	<u>Nominal</u>	<u>0 wt %</u>	<u>Nominal</u>
		<u>Gd₂O₃ pellet</u>	<u>2.5 wt % Gd₂O₃ pellet</u>	<u>Gd₂O₃ pellet</u>	<u>2.5 wt % Gd₂O₃ pellet</u>
--	0.144	0.936 ± 0.017	0.421 ± 0.002	0.925 ± 0.012	0.413 ± 0.002
0.144	0.292	0.973 ± 0.013	0.509 ± 0.002	0.945 ± 0.010	0.501 ± 0.001
0.292	0.406	1.000 ± 0.011	1.000 ± 0.003	1.000 ± 0.008	1.000 ± 0.001

Table 5-9. Relative Flux Traverse Across Position E9S9

<u>East-west traverse</u>				<u>North-south traverse</u>			
<u>Location</u>	<u>Flux</u>		<u>Ratio</u>	<u>Location</u>	<u>Flux</u>		<u>Ratio</u>
	<u>0 wt % Gd₂O₃ in fuel pellets</u>	<u>Nominal 2.5% Gd₂O₃ in fuel pellets</u>			<u>0 wt % Gd₂O₃ in fuel pellets</u>	<u>Nominal 2.5% Gd₂O₃ in fuel pellets</u>	
E1,S9	1.357	1.378	1.02	S1,E9	1.345	1.366	1.02
E2,S9	1.349	1.379	1.02	S2,E9	1.364	1.363	1.00
E3,S9	1.355	1.365	1.01	S3,E9	1.350	1.325	0.98
E4,S9	1.352	1.341	0.99	S4,E9	1.344	1.337	0.99
E5,S9	1.311	1.267	0.97	S5,E9	1.334	1.331	1.00
E6,S9	1.300	1.293	0.99	S6,E9	1.405	1.389	0.99
E7,S9	1.292	1.271	0.98	S7,E9	1.351	1.308	0.97
E8,S9	1.292	1.216	0.94	S8,E9	1.310	1.223	0.93
E9,S9	1.270	0.974	0.77	S9,E9	1.270	0.974	0.77
E10,S9	1.261	1.115	0.88	S10,E9	1.245	1.160	0.93
E11,S9	1.255	1.203	0.96	S11,E9	1.236	1.211	0.98
E12,S9	1.234	1.201	0.97	S12,E9	1.225	1.207	0.99
E13,S9	1.220	1.187	0.97	S13,E9	1.196	1.191	1.00
E14,S9	1.181	1.165	0.99	S14,E9	1.167	1.170	1.00
E15,S9	1.163	1.168	1.00	S15,E9	1.159	1.143	0.99
E16,S9	1.143	1.134	0.99	S16,E9	1.127	1.114	0.99

Table 5-10. Relative Flux Traverse Across Position E2S7

East-west traverse				North-south traverse			
Location	Flux		Ratio	Location	Flux		Ratio
	0 wt % Gd ₂ O ₃ in fuel pellets	Nominal 2.5% Gd ₂ O ₃ in fuel pellets			0 wt % Gd ₂ O ₃ in fuel pellets	Nominal 2.5% Gd ₂ O ₃ in fuel pellets	
W6,S7	1.326	1.344	1.01	N1,E2	1.532	1.487	0.97
W5,S7	1.364	1.346	0.99	N0,E2	1.518	1.510	0.99
W4,S7	1.395	1.381	0.99	S1,E2	1.486	1.466	0.99
W3,S7	1.443	1.436	1.00	S2,E2	1.477	1.461	0.99
W2,S7	1.409	1.427	1.01	S3,E2	1.518	1.487	0.98
W1,S7	1.393	1.414	1.02	S4,E2	1.458	1.430	0.98
W0,S7	1.454	1.488	1.02	S5,E2	1.457	1.412	0.97
E1,S7	1.426	1.335	0.94	S6,E2	1.471	1.375	0.93
E2,S7	1.415	1.046	0.74	S7,E2	1.415	1.046	0.74
E3,S7	1.454	1.275	0.88	S8,E2	1.384	1.260	0.91
E4,S7	1.443	1.374	0.95	S9,E2	1.351	1.316	0.97
E5,S7	1.405	1.373	0.97	S10,E2	1.364	1.338	0.98
E6,S7	1.342	1.295	0.96	S11,E2	1.387	1.407	1.01
E7,S7	1.353	1.336	0.99	S12,E2	1.357	1.357	1.00
E8,S7	1.361	1.346	0.99	S13,E2	1.315	1.316	1.00
E9,S7	1.345	1.333	0.99	S14,E2	1.290	1.295	1.00

Figure 5-1. Core XIV

○ — Water-Filled Position

● — Perturbing Pin

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