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PATHFINDER ATOMIC POWER PLANT

CLUSTERED PIN SUPERHEATER

LATTICE EXPERIMENTS

February 12, 1963

MASTER

Submitted to
U. S. ATOMIC ENERGY COMMISSION
NORTHERN STATES POWER COMPANY
and
CENTRAL UTILITIES ATOMIC POWER ASSOCIATES

by

ALLIS-CHALMERS MANUFACTURING COMPANY
ATOMIC ENERGY DIVISION
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CLUSTERED PIN SUPERHEATER LATTICE EXPERIMENTS

by A. Selep

Submitted to

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NORTHERN STATES POWER COMPANY
and
CENTRAL UTILITIES ATOMIC POWER ASSOCIATES

by

ALLIS-CHALMERS MANUFACTURING COMPANY

Under

Agreement dated 2nd Day of May 1957, as Amended
between

Allis-Chalmers Mfg. Co. & Northern States Power Co.
under

AEC Contract No. AT(11-1)-589

February 12, 1963

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Summary Report

PATHFINDER ATOMIC POWER PLANT

CLUSTERED PIN SUPERHEATER LATTICE EXPERIMENTS

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FOREWORD

This report on experiments to determine clustered pin superheater lattice constants is one of a series of reports on research and development in connection with the design of Pathfinder Atomic Power Plant.

The Pathfinder plant will be located at a site near Sioux Falls, South Dakota, and is scheduled for operation in 1963. Owners and operators of the plant will be the Northern States Power Company of Minneapolis, Minnesota. Allis-Chalmers is performing the research, development and design as well as being responsible for plant construction. The reactor will be of the controlled Recirculation Boiling Reactor type with Nuclear Superheater.

The U.S. Atomic Energy Commission, through Contract No. AT(11-1)-589 with Northern States Power Company, and Central Utilities Atomic Power Associates (CUAPA) are sponsors of the research and development program.

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1.0 INTRODUCTION

In conjunction with Pathfinder Power Plant design, Allis-Chalmers has conducted comprehensive experiments. The experiments were performed to obtain basic lattice constants which are not easily calculable with existing analytical methods, and to confirm existing analytical techniques. The experiments were performed at the Allis-Chalmers Critical Facility located in Greendale, Wisconsin on a mock-up of the Pathfinder core.

This report deals with the second generation core, specifically, with an advanced superheater design loaded with low enrichment fuel. Experiments on the first generation core are reported in Reference 1.

This report describes measurements required for calculation of the resonance escape probability (p , 28), and thermal utilization (f) in U-238.

Fuel elements in the first generation superheater core will contain fully enriched uranium dioxide fuel in stainless steel cermet, clad with stainless steel in the form of two concentric fuel tubes. Fuel elements in the boiler region will contain slightly enriched uranium dioxide pellets in Zircaloy-2 tubes.

The second generation core will use a superheater region loaded with low enriched fuel of about 4 per cent U-235. The fuel element geometry will be a seven pin cluster type.

Experimental results are given for three different fuel enrichments, 3.5 per cent, 4.0 per cent and 7.0 per cent, and for three lattice spacings each. For the 3.5 per cent and 7.0 per cent enrichments, results are

also given for a six pin cluster; i.e., with the center pin removed.

2.0 OBJECTIVE

Purpose of the experiments described in this report was to obtain detailed thermal flux distribution within a unit fuel cell, and sub-cadmium and epi-cadmium U-238 absorption in the fuel rods. These quantities are required for determination of the thermal utilization and resonance escape probability of the fuel loading.

3.0 CONCLUSION

The data gathered from the experiments presented in this report will be analyzed, and reported in "Analysis of Clustered Pin Superheater Lattice Experiments" ACNP-62022.

4.0 DESCRIPTION OF COMPONENTS AND EXPERIMENTAL PROCEDURES

4.1 Component Description

4.1.1 Core

The Pathfinder reactor core mock-up is approximately a right circular cylinder 6 ft in dia. and 6 ft high. It is made up of two regions: a superheater region in the center and the boiler region in the outer annulus (Fig. 1). Twenty cruciform boron steel control rods provide effective control over all parts of the core. The diameter of the superheater region is about 2.5 ft. It contains provisions for 428 fuel elements which are inserted into 9 ft long stainless steel outer housing tubes with 1.150 in. o.d. and 0.020 in. wall. The bottom end of this tube is closed and has a nozzle that positions the element accurately in the bottom grid plate. A tube sheet above the core properly spaces the upper end of the elements.

For this experiment the boiler core was loaded with 96 fuel elements. A boiler fuel element consists of four fuel bundles loaded axially into a 5.218 in. square box, 7 ft 6 in. long (Fig. 2).

With the above described boiler core, all control rods except two regulating rods were fully withdrawn.

The experiment, herein described, was conducted in the radial geometric center of the superheater (Fig. 1) at a test plane about 18 in. below the top of the core. The source tube, which rises to the middle of the core, is located in this position.

ITEM	BOILER CORE	SUPERHEATER CORE
NO. OF ELEMENTS	96	428
ELEMENT ASSEMBLY	8 X 8 PINS/BUNDLE-UPPER HALF 9 X 9 PINS/BUNDLE-LOWER HALF	348-2 FUEL TUBES 80-LOW ENRICHMENT
ENRICHMENT	1.89 AVERAGE	348-93.5% U235 80-LOW ENRICHMENT
LATTICE POISON	AVERAGE OF 4.42 B-AI SHEETS	SS POISON RODS IN 93.5% ELEMENTS
VOID DISTRIBUTION	NONE	FLOODED ELEMENTS UNFLOODED ELEMENTS O
CRITICAL POSITIONS RR*1 NOT USED RR*2 RR*3	SIMILAR TO EXP* RUN*	NOTES: 1. 5 B-AI SHEETS 2. 3 B-AI SHEETS 3. LOW ENRICHMENT SUPERHEATER SECTION IS CROSSHATCHED

Figure 1 - Core Layout (43-025-286)

VIEW AA

QTY	IT	DESCRIPTION	MATERIAL	PART NUMBER	WT.
1		CF FUEL ELEMENT ASSEM. (BOILER SECTION)		43-500-622	501
2		CF FUEL ELEMENT SHELL ASSEMBLY		43-500-621	501
36		TUBE SPACER ASSEMBLY (9x9 BUNDLE)		43-301-217	501
16		TUBE SPACER ASSEMBLY (8x8 BUNDLE)		43-301-218	501
14		TUBE SPACER ASSEMBLY (7x7 BUNDLE)		43-301-219	501
275		FUEL TUBE ASSEMBLY		43-301-161	501
8		SIMULATOR		43-301-216	001
36		TUBE SPACER ASSEMBLY (9x9 BUNDLE)		43-301-313	501
16		TUBE SPACER ASSEMBLY (8x8 BUNDLE)		43-301-311	501
14		TUBE SPACER ASSEMBLY (7x7 BUNDLE)		43-301-312	501

Sufficient space remains above the source tube for a half-length element. A test assembly was designed for this location and the experiment conducted in its mid-section. During all the runs a minimum of 5 x 5 element lattice surrounding the test element was always loaded to match the test element. It is considered that the 5 x 5 element lattice provides sufficient distance to make the spectrum effect of the outer loading negligible at the test element. The 9 x 9 element section, which includes the test assembly has elements spaced on a 1-1/4 in. square grid. This 9 x 9 element section was loaded with the low enrichment fuel, specifically, a seven fuel rod cluster enriched with 3.5 per cent u-235. The remainder of the superheater core was loaded with the high enrichment fuel elements with a central stainless steel poison rod. (Fig. 3).

4.1.2 Low Enrichment Fuel

The low enrichment superheater fuel consists of 0.214 in. dia. UO_2 pellets loaded in stainless steel tubes with 0.010 in. walls. The total length of these rods is 36-1/8 in. and the active fuel length is 35-7/8 in. The density of uranium dioxide in the fuel rods is 95 per cent of theoretical. These rods are grouped into bundles of seven fuel rods in a hexagonal array with a central rod. A fuel element is made up of two of these bundles loaded end-to-end into a stainless steel container tube (0.010 in. o.d. x 0.023 in. wall) making an active fuel length of 6 ft (Fig. 4). This, in turn, is placed into the 9 ft long 1.150 in. o.d. outer housing tube, described at the beginning of this section.

SECTION AA

MK 501 REQ	IT	DESCRIPTION	MAT'L	PART NUMBER	DRAWING MK	WT
1	1	SUPERHEATER FUEL ELEMENT ASSY		43-500-603	501	#F
1	2	TUBE ASSEMBLY		43-400-871	501	
1	3	FUEL TUBE ASSEMBLY		13-500-602	501

Figure 3 - High Enrichment Superheater Fuel Element (43-500-603)

4.1.3 Test Assembly

The test assembly is made up of a half-length fuel element, i.e., with a test element of one fuel bundle, accurately positioned in a test element holder. The test assembly can be accurately positioned in the core and easily removed. The test element holder is fabricated from the same material and has the same radial dimensions as the outer housing tube of the standard superheater element. It is positioned and positively supported by 2 tube sheets, so that an accurate and reproducible fuel element spacing is obtained. A 1/4 in. plate, made to resemble a section of the upper tube sheet, is welded to the test element holder, and spaces the fuel elements at the upper end. An auxiliary tube sheet of Lucite is attached to the eight surrounding fuel elements, and properly spaces them about 1 in. below the test plane.

The seven fuel rod cluster test element is oriented and held concentric by spacers at each end of the fuel bundle and 1 in. above and below the test plane. By using different lattice spacers the centers of the outer fuel rods can be located on circles of 0.2785 in., 0.325 in. or 0.375 in. radii, concentric with the center fuel rod, for the "B", "C", and "D" lattices respectively. The end spacers are of aluminum. The spacers near the test plane are of aluminum for the voided case, and of Lucite for the flooded case. The orientation of the test element within the test element holder is ensured by a keyway on the periphery of the spacers, and by a wire key welded, full length, to the inside of the test element holder. The test element

and the test element holder are shown in Figure 5.

Three fuel rods of the test element fuel cluster are provided with studs at each end and are affixed to the end spacers by nuts. The other four fuel rods are cut in two, establishing a test plane perpendicular to the axis of the element. The cut ends are ground flat and square. The container tube has also been sectioned so that it fits between the spacers of the test element. Thus, the test element contains all the components of a normal element. Located on the outside of the test element holder is a 1-1/4 in. square Lucite platform, which within its boundaries represents a unit cell. The top of this platform is at the test plane.

4.2 Experimental Procedures

The resonance escape probability in U-238 (p^{28}) is defined by the formula $(1-p^{28})/p^{28} = p^{28} fR$ (Ref. 2)

where:

- p^{28} - is the ratio of epi-cadmium to sub-cadmium absorption in the fuel
- f - is the thermal utilization of the lattice
- R - is the ratio of radiative thermal capture in U-238 to total thermal capture in the fuel.

The thermal utilization (f) of the lattices is calculated using region-wise thermal flux values, and the appropriate volumes and cross sections.

The U-238 to total thermal capture ratio (R) is obtained using published cross-sections of the fuel ingredients averaged over the thermal spectrum

Figure 5 - Test Element and Test Element Holder (215548)

by the SOFOCATE routine (Ref. 2). The experimental determination of p^{28} then is dependent on the measurement of the sub-cadmium fluxes in the fuel and moderator, and of epi- and sub-cadmium U-238 radiative capture ratio, and other cell components. Experimental procedures for each of the above is different, therefore they will be described separately.

4.2.1 Flux Measurement

To determine flux distribution in the fuel cell, a measurement plane was established perpendicular to the axis of the element, and thin fission foil was placed in this plane. The foil was irradiated with the assembly, then cut into regions for which flux information was required. The fission product activity was then measured.

The thin (0.005 in.) U-Al foil (Fig. 6) was slipped over the unsectioned rods and placed at the test plane, with the sectioned fuel rods and container tube butting squarely against each side of the foil. The foil size is such that it just fits into the test element holder. On the Lucite platform a square U-Al foil was mounted which, with the foil in the fuel region, covers the entire cross sectional area of the unit cell, with the exception of the test element holder wall thickness. The foils as mounted are shown in Fig. 7.

The test element placed in the test element holder was irradiated in the reactor for one hour and then counted for fission product Beta activity. The reactor power level was adjusted to give a counting rate of about 10,000 counts per second per cm^2 of foil one half hour after shutdown. The reactor power level was adjusted for 100 watts with voided and 50 watts with flooded superheater. This counting rate

Figure 7 - Foils as Mounted on Test Section (215546)

is sufficiently high to give good statistics and still maintain a negligible dead time correction. To prevent fission products from adhering to the U-Al foil from the butting fuel rods, and thus adding to its total activity the fuel region foil was taped on each side. The tape was stripped before counting.

Following irradiation, four discs of 0.237 in. dia. were punched from the fuel region foil, corresponding to the locations of the butting fuel rods. The remainder of this foil was cut into concentric rings of radii listed in Table I, and mounted with tape on planchettes for counting as shown in Figure 8.

TABLE I FUEL CLUSTER FOIL RING DIMENSIONS

<u>Region</u>	<u>Outer Radius Inches</u>
Center Fuel Rod	0.119
Outer Fuel Rods (Radius of Centers)	
Lattice B	(0.287)
Lattice C	(0.325)
Lattice D	(0.375)
Ring 1	0.185
Ring 2	0.236
Ring 3	0.311
Ring 4	0.361
Ring 5	0.410
Ring 6	0.460
Ring 7	0.552
Moderator (Effective Radius)	(0.705)

The foil on the platform of the test element holder was quartered and each quarter placed on two planchettes; 0.237 in. dia. disc on one and the remainder on the other, as shown in Figure 8. About 30 minutes was required for this operation, and counting began within 45 minutes of reactor shutdown. The activity counted was the average over the following cell regions:

1. the central fuel rod (for the seven-rod cluster) or the central space (for the six-rod cluster)
2. the six outer fuel rods
3. seven concentric rings listed in Table 1.
4. the moderator region exterior to the outer housing tube.

Volume fractions of these cell regions are given in Table 2 for the three lattices "B", "C", and "D". The areas of the various rings represent the ring area minus the area occupied by the fuel rods in that ring, if any. As the fuel rod spacing changes from "B" to "C" to "D" lattice the area left in the rings will vary. However, their position with respect to the cell center remains the same.

The foils were counted sequentially for gross fission product Beta activity for six to eight cycles against a decay foil of the same material and exposed to the same irradiation as the above foils. This method eliminates the need for decay correction, which is especially difficult for fission products because of the variable half life.

All foils were then allowed to decay at least a week and were re-exposed to the same integrated neutron flux by spinning. The Beta activity was

Figure 8 - Division of Foils for Counting (215545)

TABLE 2. VOLUME FRACTIONS OF FUEL CELL REGIONS

<u>Region</u>	<u>B Lattice</u>	<u>C Lattice</u>	<u>D Lattice</u>
Each fuel pin	0.02888	0.02888	0.02888
Ring 1	0.03448	0.04196	0.04196
Ring 2	0.01646	0.02875	0.04312
Ring 3	0.03248	0.03855	0.05487
Ring 4	0.02621	0.03110	0.03611
Ring 5	0.03393	0.03534	0.04103
Ring 6	0.08945	0.05730	0.04705
Ring 7	0.24478	0.24478	0.21364
Moderator Region	0.32008	0.32008	0.32008

The Beta activity was re-counted against the same decay foil, with the foils in the same geometry as in the initial counting. This was done to correct for the following:

1. counter geometry differences between foils
2. foil size differences
3. U-235 inhomogeneity within the foils.

The data was then corrected for counter dead time and drift, and averaged. By irradiating the decay foil in the same flux as the other foils, no background correction is required. Measurement of the flooded and voided cadmium ratios allowed the fast flux (which was assumed to be constant over the cell) to be subtracted from the total flux, leaving the thermal flux. The foils were then flux-normalized to a value of 1 at the center of the cell. The results are given in Tables 3 through 12.

TABLE 3 RELATIVE FLUX IN VOIDED SUPERHEATER
CELL WITH 7 ROD 3.5% FUEL

<u>Region</u>	<u>B-Lattice</u> <u>(Run 39-98)</u>	<u>C-Lattice</u> <u>(Run 39-117)</u>	<u>D-Lattice</u> <u>(Run 39-115)</u>
Center Fuel Rod	1.0000 $\pm$ 0.0063	1.0000 $\pm$ 0.0051	1.0000 $\pm$ 0.0051
Outer Fuel Rod	1.0813 $\pm$ 0.0061	1.0645 $\pm$ 0.0084	1.0597 $\pm$ 0.0062
Ring 1	1.0399 $\pm$ 0.0035	1.0553 $\pm$ 0.0040	1.0656 $\pm$ 0.0037
Ring 2	1.0690 $\pm$ 0.0069	1.0494 $\pm$ 0.0044	1.0770 $\pm$ 0.0061
Ring 3	1.1120 $\pm$ 0.0081	1.0720 $\pm$ 0.0044	1.0845 $\pm$ 0.0045
Ring 4	1.1817 $\pm$ 0.0045	1.1209 $\pm$ 0.0068	1.1107 $\pm$ 0.0070
Ring 5	1.2308 $\pm$ 0.0035	1.1620 $\pm$ 0.0037	1.1348 $\pm$ 0.0069
Ring 6	1.2793 $\pm$ 0.0062	1.1988 $\pm$ 0.0056	1.1823 $\pm$ 0.0043
Ring 7	1.3268 $\pm$ 0.0076	1.2560 $\pm$ 0.0063	1.2239 $\pm$ 0.0045
Moderator Region	1.6495 $\pm$ 0.0062	1.5666 $\pm$ 0.0072	1.5099 $\pm$ 0.0071
Cell Average	1.3499	1.2825	1.2502

TABLE 4 RELATIVE FLUX IN FLOODED SUPERHEATER
CELL WITH 7 ROD 3.5% FUEL

<u>Region</u>	<u>B-Lattice</u> <u>(Run 39-104)</u>	<u>C-Lattice</u> <u>(Run 39-102)</u>	<u>D-Lattice</u> <u>(Run 39-106)</u>
Center Fuel Rod	1.0000 $\pm$ 0.0045	1.0000 $\pm$ 0.0070	1.0000 $\pm$ 0.0052
Outer Fuel Rod	1.1186 $\pm$ 0.0053	1.1168 $\pm$ 0.0068	1.0748 $\pm$ 0.0063
Ring 1	1.0822 $\pm$ 0.0035	1.1103 $\pm$ 0.0063	1.1060 $\pm$ 0.0056
Ring 2	1.1275 $\pm$ 0.0057	1.1190 $\pm$ 0.0062	1.1378 $\pm$ 0.0066
Ring 3	1.1714 $\pm$ 0.0054	1.1564 $\pm$ 0.0069	1.1414 $\pm$ 0.0047
Ring 4	1.2677 $\pm$ 0.0062	1.2082 $\pm$ 0.0072	1.1596 $\pm$ 0.0079
Ring 5	1.3536 $\pm$ 0.0054	1.2728 $\pm$ 0.0062	1.1873 $\pm$ 0.0065
Ring 6	1.4507 $\pm$ 0.0081	1.3101 $\pm$ 0.0044	1.2369 $\pm$ 0.0067
Ring 7	1.5251 $\pm$ 0.0027	1.3975 $\pm$ 0.0096	1.2773 $\pm$ 0.0049
Moderator Region	1.7350 $\pm$ 0.0067	1.6185 $\pm$ 0.0062	1.4518 $\pm$ 0.0068
Cell Average	1.4546	1.3917	1.2595

**TABLE 5 RELATIVE FLUX IN VOIDED SUPERHEATER
CELL WITH 7 ROD 4% FUEL**

<u>Region</u>	<u>B-Lattice (Run 39-310)</u>	<u>C-Lattice (Run 39-309)</u>	<u>D-Lattice (Run 39-311)</u>
Center Fuel Rod	1.0000 $\pm$ 0.0046	1.0000 $\pm$ 0.0042	1.0000 $\pm$ 0.0051
Outer Fuel Rod	1.1860 $\pm$ 0.0060	1.1474 $\pm$ 0.0052	1.1400 $\pm$ 0.0047
Ring 1	1.0972 $\pm$ 0.0044	1.1160 $\pm$ 0.0049	1.1307 $\pm$ 0.0038
Ring 2	1.2096 $\pm$ 0.0083	1.1226 $\pm$ 0.0045	1.1495 $\pm$ 0.0051
Ring 3	1.1494 $\pm$ 0.0090	1.2173 $\pm$ 0.0038	1.1621 $\pm$ 0.0043
Ring 4	1.2977 $\pm$ 0.0090	1.1634 $\pm$ 0.0043	1.1877 $\pm$ 0.0037
Ring 5	1.3683 $\pm$ 0.0062	1.2685 $\pm$ 0.0049	1.2185 $\pm$ 0.0048
Ring 6	1.4108 $\pm$ 0.0065	1.3305 $\pm$ 0.0046	1.2565 $\pm$ 0.0077
Ring 7	1.4604 $\pm$ 0.0063	1.3902 $\pm$ 0.0063	1.3164 $\pm$ 0.0060
Moderator Region	1.8259 $\pm$ 0.0071	1.7460 $\pm$ 0.0077	1.6681 $\pm$ 0.0066
Cell Average	1.4789	1.4104	1.3554

**TABLE 6 RELATIVE FLUX IN FLOODED SUPERHEATER
CELL WITH 7 ROD 4% FUEL**

<u>Region</u>	<u>B-Lattice (Run 39-313)</u>	<u>C-Lattice (Run 39-314)</u>	<u>D-Lattice (Run 39-315)</u>
Center Fuel Rod	1.000 $\pm$ 0.0041	1.0000 $\pm$ 0.0039	1.0000 $\pm$ 0.0040
Outer Fuel Rod	1.2629 $\pm$ 0.0047	1.2452 $\pm$ 0.0046	1.2095 $\pm$ 0.0047
Ring 1	1.1621 $\pm$ 0.0044	1.1930 $\pm$ 0.0042	1.1953 $\pm$ 0.0077
Ring 2	1.2363 $\pm$ 0.0068	1.2546 $\pm$ 0.0067	1.2551 $\pm$ 0.0048
Ring 3	1.3058 $\pm$ 0.0057	1.3079 $\pm$ 0.0048	1.2794 $\pm$ 0.0045
Ring 4	1.4243 $\pm$ 0.0054	1.3820 $\pm$ 0.0039	1.3178 $\pm$ 0.0067
Ring 5	1.5304 $\pm$ 0.0043	1.4596 $\pm$ 0.0033	1.3562 $\pm$ 0.0096
Ring 6	1.6257 $\pm$ 0.0056	1.5245 $\pm$ 0.0059	1.4036 $\pm$ 0.0054
Ring 7	1.7489 $\pm$ 0.0041	1.6299 $\pm$ 0.0059	1.4454 $\pm$ 0.0068
Moderator Region	1.9940 $\pm$ 0.0073	1.8554 $\pm$ 0.0062	1.6832 $\pm$ 0.0066
Cell Average	1.6511	1.5538	1.4300

**TABLE 7 RELATIVE FLUX IN VOIDED SUPERHEATER
CELL WITH 7 ROD 7% FUEL**

<u>Region</u>	<u>B-Lattice</u> <u>(Run 39-196)</u>	<u>C-Lattice</u> <u>(Run 39-189)</u>	<u>D-Lattice</u> <u>(Run 39-182)</u>
Center Fuel Rod	1.0000 $\pm$ 0.0048	1.0000 $\pm$ 0.0050	1.0000 $\pm$ 0.0045
Outer Fuel Rod	1.1522 $\pm$ 0.0061	1.1010 $\pm$ 0.0050	1.0815 $\pm$ 0.0070
Ring 1	1.0642 $\pm$ 0.0036	1.1011 $\pm$ 0.0043	1.1036 $\pm$ 0.0044
Ring 2	1.0880 $\pm$ 0.0096	1.0832 $\pm$ 0.0054	1.1177 $\pm$ 0.0044
Ring 3	1.2055 $\pm$ 0.0060	1.1277 $\pm$ 0.0049	1.1098 $\pm$ 0.0044
Ring 4	1.3247 $\pm$ 0.0071	1.2172 $\pm$ 0.0056	1.1614 $\pm$ 0.0061
Ring 5	1.4225 $\pm$ 0.0057	1.2847 $\pm$ 0.0063	1.2041 $\pm$ 0.0057
Ring 6	1.5243 $\pm$ 0.0058	1.3515 $\pm$ 0.0037	1.2614 $\pm$ 0.0027
Ring 7	1.5863 $\pm$ 0.0058	1.4472 $\pm$ 0.0063	1.3403 $\pm$ 0.0047
Moderator Region	2.1244 $\pm$ 0.0069	1.9512 $\pm$ 0.0080	1.8122 $\pm$ 0.0074
Cell Average	1.6099	1.4799	1.3886

**TABLE 8 RELATIVE FLUX IN FLOODED SUPERHEATER
CELL WITH 7 ROD 7% FUEL**

<u>Region</u>	<u>B-Lattice</u> <u>(Run 39-209)</u>	<u>C-Lattice</u> <u>(Run 39-208)</u>	<u>D-Lattice</u> <u>(Run 39-206)</u>
Center Fuel Rod	1.0000 $\pm$ 0.0042	1.0000 $\pm$ 0.0048	1.0000 $\pm$ 0.0038
Outer Fuel Rod	1.1893 $\pm$ 0.0052	1.1490 $\pm$ 0.0048	1.1230 $\pm$ 0.0054
Ring 1	1.1119 $\pm$ 0.0038	1.1315 $\pm$ 0.0042	1.1900 $\pm$ 0.0057
Ring 2	1.1509 $\pm$ 0.0069	1.1413 $\pm$ 0.0046	1.2364 $\pm$ 0.0052
Ring 3	1.2851 $\pm$ 0.0075	1.2020 $\pm$ 0.0052	1.2367 $\pm$ 0.0031
Ring 4	1.4433 $\pm$ 0.0067	1.3163 $\pm$ 0.0065	1.2642 $\pm$ 0.0044
Ring 5	1.5812 $\pm$ 0.0057	1.4258 $\pm$ 0.0055	1.3294 $\pm$ 0.0044
Ring 6	1.7254 $\pm$ 0.0044	1.5176 $\pm$ 0.0073	1.4126 $\pm$ 0.0048
Ring 7	1.9027 $\pm$ 0.0062	1.6795 $\pm$ 0.0060	1.4897 $\pm$ 0.0057
Moderator Region	2.2576 $\pm$ 0.0073	2.0236 $\pm$ 0.0069	1.7976 $\pm$ 0.0075
Cell Average	1.7692	1.5890	1.4548

TABLE 9 RELATIVE FLUX IN VOIDED SUPERHEATER
CELL WITH 6 ROD 3.5% FUEL

<u>Region</u>	<u>B-Lattice</u> <u>(Run 39-160)</u>	<u>C-Lattice</u> <u>(Run 39-157)</u>	<u>D-Lattice</u> <u>(Run 39-154)</u>
Center Space	1.0000 $\pm$ 0.0058	1.0000 $\pm$ 0.0036	1.0000 $\pm$ 0.0047
Outer Fuel Rod	0.9709 $\pm$ 0.0057	0.9518 $\pm$ 0.0048	0.9439 $\pm$ 0.0064
Ring 1	0.9649 $\pm$ 0.0049	0.9847 $\pm$ 0.0039	0.9767 $\pm$ 0.0055
Ring 2	0.9637 $\pm$ 0.0063	0.9607 $\pm$ 0.0068	0.9628 $\pm$ 0.0062
Ring 3	1.0022 $\pm$ 0.0091	0.9774 $\pm$ 0.0086	0.9589 $\pm$ 0.0052
Ring 4	1.0423 $\pm$ 0.0034	1.0115 $\pm$ 0.0111	0.9769 $\pm$ 0.0085
Ring 5	1.0973 $\pm$ 0.0057	1.0335 $\pm$ 0.0066	0.9892 $\pm$ 0.0082
Ring 6	1.1164 $\pm$ 0.0078	1.0575 $\pm$ 0.0040	1.0211 $\pm$ 0.0049
Ring 7	1.1559 $\pm$ 0.0058	1.1003 $\pm$ 0.0048	1.0438 $\pm$ 0.0050
Moderator Region	1.4360 $\pm$ 0.0074	1.3780 $\pm$ 0.0065	1.3128 $\pm$ 0.0076
Cell Average	1.1859	1.1393	1.0582

TABLE 10 RELATIVE FLUX IN FLOODED SUPERHEATER
CELL WITH 6 ROD 3.5% FUEL

<u>Region</u>	<u>B-Lattice</u> <u>(Run 39-167)</u>	<u>C-Lattice</u> <u>(Run 39-173)</u>	<u>D-Lattice</u> <u>(Run 39-178)</u>
Center Space	1.0000 $\pm$ 0.0056	1.0000 $\pm$ 0.0053	1.0000 $\pm$ 0.0074
Outer Fuel Rod	0.8418 $\pm$ 0.0066	0.8500 $\pm$ 0.0060	0.7956 $\pm$ 0.0052
Ring 1	0.8688 $\pm$ 0.0035	0.9625 $\pm$ 0.0038	0.9589 $\pm$ 0.0045
Ring 2	0.8683 $\pm$ 0.0079	0.9119 $\pm$ 0.0048	0.9314 $\pm$ 0.0043
Ring 3	0.8926 $\pm$ 0.0029	0.8963 $\pm$ 0.0076	0.8811 $\pm$ 0.0045
Ring 4	0.9571 $\pm$ 0.0069	0.9203 $\pm$ 0.0081	0.8759 $\pm$ 0.0082
Ring 5	1.0085 $\pm$ 0.0060	0.9488 $\pm$ 0.0076	0.8731 $\pm$ 0.0065
Ring 6	1.0606 $\pm$ 0.0047	0.9791 $\pm$ 0.0058	0.8995 $\pm$ 0.0069
Ring 7	1.1146 $\pm$ 0.0045	1.0264 $\pm$ 0.0063	0.9261 $\pm$ 0.0059
Moderation Region	1.2517 $\pm$ 0.0073	1.1763 $\pm$ 0.0063	1.0257 $\pm$ 0.0066
Cell Average	1.0756	0.9745	0.9313

**TABLE 11 RELATIVE FLUX IN VOIDED SUPERHEATER
CELL WITH 6 ROD 7% FUEL**

<u>Region</u>	<u>B-Lattice</u> <u>(Run 39-234)</u>	<u>C-Lattice</u> <u>(Run 39-223)</u>	<u>D-Lattice</u> <u>(Run 39-329)</u>
Center Space	1.0000 $\pm$ 0.0048	1.0000 $\pm$ 0.0058	1.0000 $\pm$ 0.0065
Outer Fuel Rod	0.9685 $\pm$ 0.0045	0.9146 $\pm$ 0.0048	0.8905 $\pm$ 0.0059
Ring 1	0.9533 $\pm$ 0.0046	0.9646 $\pm$ 0.0061	1.0012 $\pm$ 0.0059
Ring 2	0.9466 $\pm$ 0.0083	0.9255 $\pm$ 0.0047	0.9589 $\pm$ 0.0042
Ring 3	1.0140 $\pm$ 0.0068	0.9695 $\pm$ 0.0046	0.9462 $\pm$ 0.0051
Ring 4	1.1057 $\pm$ 0.0052	1.0172 $\pm$ 0.0066	0.9677 $\pm$ 0.0048
Ring 5	1.1801 $\pm$ 0.0052	1.0675 $\pm$ 0.0080	1.0015 $\pm$ 0.0064
Ring 6	1.2332 $\pm$ 0.0058	1.1205 $\pm$ 0.0030	1.0317 $\pm$ 0.0067
Ring 7	1.3016 $\pm$ 0.0052	1.1770 $\pm$ 0.0055	1.0988 $\pm$ 0.0059
Moderator Region	1.0975 $\pm$ 0.0074	1.5602 $\pm$ 0.0077	1.4810 $\pm$ 0.0077
Cell Average	1.2549	1.2130	1.1513

**TABLE 12 RELATIVE FLUX IN FLOODED SUPERHEATER
CELL WITH 6 ROD 7% FUEL**

<u>Region</u>	<u>B-Lattice</u> <u>(Run 39-235)</u>	<u>C-Lattice</u> <u>(Run 39-241)</u>	<u>D-Lattice</u> <u>(Run 33-333)</u>
Center Space	1.0000 $\pm$ 0.0050	1.0000 $\pm$ 0.0037	1.0000 $\pm$ 0.0047
Outer Fuel Rod	0.8868 $\pm$ 0.0043	0.8326 $\pm$ 0.0043	0.7374 $\pm$ 0.0050
Ring 1	0.9546 $\pm$ 0.0061	0.9624 $\pm$ 0.0048	0.9642 $\pm$ 0.0066
Ring 2	0.8981 $\pm$ 0.0055	0.9097 $\pm$ 0.0028	0.9019 $\pm$ 0.0073
Ring 3	0.9321 $\pm$ 0.0071	0.9037 $\pm$ 0.0055	0.8588 $\pm$ 0.0061
Ring 4	1.0467 $\pm$ 0.0045	0.9521 $\pm$ 0.0057	0.8435 $\pm$ 0.0067
Ring 5	1.1395 $\pm$ 0.0051	1.0057 $\pm$ 0.0045	0.8643 $\pm$ 0.0062
Ring 6	1.2239 $\pm$ 0.0044	1.0656 $\pm$ 0.0042	0.8957 $\pm$ 0.0053
Ring 7	1.3419 $\pm$ 0.0053	1.1599 $\pm$ 0.0039	0.9212 $\pm$ 0.0045
Moderator Region	1.5646 $\pm$ 0.0077	1.3619 $\pm$ 0.0057	1.1019 $\pm$ 0.0064
Cell Average	1.2654	1.1206	0.9372

In the tables, the value given for the outer fuel rod is the average of the three foils butting the sectioned fuel rods. The value labeled "moderator region" is the average flux in the region of the test cell external to the test section holder. The errors indicated are the most probable errors expected, consistent with the sequential counting over many cycles.

The value labeled "cell average" is the average value of thermal flux in the cell excluding the container tube wall area. It is rather difficult to assign a flux value to the container tube because region integral fluxes were measured in the cell. If there were reasonable symmetry within the cell, the average flux in the container tube could be determined by interpolation with acceptable accuracy. However, with the unusual geometry of this fuel cell, where the moderator is essentially localized in an area between four fuel tubes, a large azimuthal variation in the flux is found at the inner moderator boundary. Since the average of this variation is not necessarily reflected in the moderator flux average, the housing tube flux cannot be accurately interpolated. Because the cross sectional area of the container is only about 6 per cent of the total cell area, and since the flux in the container tube appears to be near the average value, the error resulting from assuming it to be at the average is within the error quoted in the tables.

The same results are shown graphically in Figures 9 through 18. Each figure shows the region average fluxes for the B, C, and D lattice of

Figure 9 - Relative Flux in Voided Superheater Cell 7 Rod 3.5% Fuel (43-025-127)

Figure 10 - Relative Flux in Flooded Superheater Cell with 7 Rod 3.5% Fuel (43-025-129)

Figure 11 - Relative Flux in Voided Superheater Cell with 7 Rod 4% Fuel (43-025-264)

Figure 12 - Relative Flux in Flooded Superheater Cell with 7 Rod 4% Fuel (43-025-263)

Figure 13 - Relative Flux in Voided Superheater Cell with 7 Rod 7% Fuel (43-025-130)

Figure 14 - Relative Flux in Flooded Superheater Cell with 7 Rod 7% Fuel (43-025-128)

Figure 15 - Relative Flux in Voided Superheater Cell with 6 Rod 3.5% Fuel (43-025-131)

Figure 16 - Relative Flux in Flooded Superheater Cell with 6 Rod 3.5% Fuel (43-025-132)

Figure 17 - Relative Flux in Voided Superheater Cell with 6 Rod 7% Fuel (43-025-266)

Figure 18 - Relative Flux in Flooded Superheater Cell with 6 Rod 7½ Fuel (43-025-265)

the test case presented. The points are plotted at the radial center of the corresponding regions. Because it is difficult to assign regions to the outer fuel rods, their average flux value has been included as a separate point for each case. It should be noted that the flux in the fuel rods is appreciably below that of the ring segment at the same radius, as expected, due to depression in the fuel.

Figures 19, 20, and 21 show four flux ratio curves for both voided and flooded cases, each as a function of lattice spacing, for 7-rod cluster fuel of 3.5, 4.0 and 7.0 per cent enrichment respectively.

The ratios represent:

1. flux in outer fuel rods to that in center fuel rod
2. flux in moderator to that in center fuel rod
3. flux in moderator to that in outer fuel rods
4. flux in moderator to that in total fuel.

The last ratio is also called a disadvantage factor of cell, and is plotted separately in Figure 22 as a function of enrichment. Figures 23 and 24 show flux ratios for the six-rod cases with 3.5 and 7.0 per cent fuel respectively. Since there is no fuel rod in the center of the cluster, the ratios are made with respect to the center space. The outer fuel is the total fuel so only three curves are shown for each case. The disadvantage factor for six-rod cases is plotted as a function of enrichment in Figure 25.

Figure 26 shows the ratio of the average thermal flux in a 7-rod cluster fuel cell to that in the moderator region as a function of

Figure 19 - Flux Ratios in 7 Rod 3.5% Fuel Cell (43-025-269)

Figure 20 - Flux Ratios in 7 Rod 4% Fuel Cell (43-025-280)

Figure 21 - Flux Ratios in 7 Rod 7% Fuel Cell (43-025-281)

Figure 22 - Disadvantage Factors for 7 Rod Cluster Fuel Cell (43-025-282)

Figure 23 - Flux Ratios in 6 Rod 3.5% Fuel Cell (43-025-261)

Figure 24 - Flux Ratios in 6 Rod 7% Fuel Cell (43-025-262)

Figure 25 - Disadvantage Factors for 6 Rod Cluster Fuel Cell (43-025-283)

Figure 26 - Average Thermal Flux in 7 Rod Cluster Fuel Cell (43-025-284)

enrichment. This ratio appears to be only slightly dependent on lattice spacing and therefore only one curve each is plotted for voided and flooded cases, respectively.

The cadmium ratio of the cell as a function of enrichment for voided and flooded cases respectively is plotted in Figure 27. This ratio as given herein is defined as average total flux of the cell to the fast flux. It was experimentally shown that the cadmium ratio of the cell is independent of lattice spacing. It is interesting to note from the graph that this cadmium ratio is a linear function of the enrichment.

4.2.2 Sub- and Epi-Cadmium U-238 Absorption

To measure the sub- and epi-cadmium U-238 absorption in the fuel, highly depleted uranium foils with either cadmium or aluminum covers, were placed between fuel pellets of a stack composing a fuel rod. Following irradiation, the 74 kev gamma ray from U-239 decay was counted, giving the relative neutron absorption in U-238.

The radiative neutron capture in U-238 yields the following reaction:

where the energy level of the γ emitted by U-238 in decaying to Np-239 is 73.6 kev. This radiation, which is proportional to the radiative capture in U-238 is used to obtain measurements of p^{28} .

The method by which this was accomplished is to irradiate a cadmium-covered and an uncovered highly depleted U-238 foils (3 to 5 ppm of U-235) and measure the subsequent 73.6 kev radiation. Highly

Figure 27 - Cadmium Ratio of 7 Rod Cluster Fuel Cell (43-025-285)

depleted uranium foils are used also to monitor integrated exposure, which is used to normalize the data for the cadmium-covered and the uncovered runs.

The foils are inserted into pellet packages. Two types of pellet packages are used. The cadmium-covered pellet package, which is used to measure epi-cadmium U-238 radiative capture, consists of the highly depleted uranium foil, 0.214 in. dia., sandwiched between 0.174 in. thick oxide pellets identical to the fuel tube pellets. This package is surrounded by a 0.020 in. thick cylinder of cadmium and is capped by 0.020 in. thick cadmium. A layout and photograph of the package are shown in Figures 4 and 29.

The "uncovered" pellet package, which is used to measure the total U-238 radiative capture, is identical to the cadmium-covered pellet package except that the cadmium components are replaced by aluminum. The aluminum is necessary to displace the same amount of water as the cadmium for the flooded lattice case, however, it does not act as a filter.

Figures 28 and 29 show aluminum catcher foils on each side of the depleted U-238 foil. Initially these were used to catch the fission recoil products from the neighboring fuel pellets, which would increase the measured activity of the depleted foil after irradiation. Since the photographs were taken, it has been discovered that these aluminum foils caused a significant increase of U-239 activity in the depleted foil. This increase was measured by covering several depleted uranium

Figure-28 - Test Section for Measurement of Epi-Cadmium U-238 Absorption (43-024-844)

Figure 29 - Components of Pellet Package for Measurement of U-238 Absorption (215549)

foils with various thicknesses of aluminum, inserting them into pellet packages and exposing them to the same integrated flux. The resultant U-239 activity showed an increase corresponding to about one per cent per 0.001 in. thick aluminum foil for the cadmium covered package and about 1/3 of that for the aluminum covered package. This U-239 activity increase is caused by the streaming of resonance energy neutrons through the aluminum, which in effect increases the surface area of the depleted foil. Moreover, since neither cadmium nor aluminum filter the resonance energy neutrons, the magnitude of increase for either should be the same.

Because of this effect, and the possible difficulty in keeping close control of the separation of the fuel pellets and the depleted foil with aluminum located between, subsequent measurements have been performed without the aluminum catcher foil. The resultant activity was then corrected for the fission recoil products from the fuel pellet. The correction was experimentally determined by irradiating aluminum foil in contact with fuel pellets. The resultant fission product activity, caught on the aluminum, was then counted as a function of time using the same spectrometer setup as used for the U-239 counting. This activity was then subtracted, as background, from the U-239 activity of the depleted foils. The correction was small for the cadmium covered foils, where few fissions take place in the pellet package.

The pellet packages were inserted in the test assembly (Fig. 30 and 31). The test assembly was then inserted in the central location in

Figure 30 - Low Enrichment Superheater Fuel Bundle (Compact Lattice) (215377)

Figure 31 - Low Enrichment Superheater Fuel Bundle (Expanded Bundle) (215380)

the reactor. The pellet packages were inserted in such a manner that there was continuity of fuel in the lattice except for the cover and foils. The perturbation caused by the pellet packages was therefore kept to a minimum. Foils of highly depleted uranium were placed in the lattice to monitor the integrated exposure for normalization.

Three lattice spacings were used for the experiment, the same ones as for the flux distribution measurement; namely, with the outer fuel rods located on circles with a 0.2875 in., 0.325 in., and 0.375 in. radius, concentric with the center fuel rod, for the "B", "C" and "D" lattices respectively.

With the test section and monitors in place, the foils were irradiated at 100 watts for 45 min., were removed after shutdown, and counting was initiated 5 min. after shutdown.

The 73.6 kev activities were measured with a scintillation spectrometer consisting of a 2 by 2 in NA(Tl) crystal mounted on a 6292 photomultiplier connected to a cathode follower, non-overloading linear amplifier, pulse-height analyzer, gated scaler, and a decimal printer. The pulse-height analyzer was set at a base line of 68.5 kev with a window width of 10 kev. The equipment resolution of the U-239 73.6 kev gamma is about 15 per cent.

Timing was accomplished by using the output of a 1000 cps (± 0.002 cps) tuning-fork oscillator in a pre-set counter that gates the counting

of the scaler. Each foil counting period was 60.1 sec.; 11.1 sec. was allowed for change of sample. The foils were counted for 9 cycles, which is approximately 3 half-lives for a 3-foil (plus three-monitor-foil) measurement.

The data obtained from the counting was corrected for a background as measured prior to the irradiation, with the same spectrometer settings. The resulting activities were then checked for half-life. No systematic deviations from the expected 23.5 min. half-life were found in any of the data counted in this manner.

The data for each foil was fitted by the least square fit method to a 23.5 min. half-life curve, and the activity was corrected back to the shutdown time. For a given irradiation, this yields the relative activity of the U-238 in the test foils at shutdown. Normalization between irradiations was accomplished by using the corrected activities of the monitor foils which were placed in the lattice so that changes in the pellet packages would not affect their activities.

The measured U-238 activity for the various lattices and enrichment is shown graphically in Figures 32 through 35, and the corresponding Rho values are given in Table 13. It is interesting to note that the ratio of voided-to-flooded Rho value remains nearly constant, and is $1.700 \pm 6\%$ for the outer fuel rods, and $1.600 \pm 4.5\%$ for the central fuel rods.

TABLE 13 VALUES OF ρ ²⁸ 7 ROD 3.5%

<u>Lattice</u>		<u>Outer Fuel Rods</u>	<u>Center Fuel Rods</u>
B	Voided	2.79 ± 0.11	2.53 ± 0.10
	Flooded	1.62 ± 0.07	1.56 ± 0.06
C	Voided	2.70 ± 0.11	2.69 ± 0.11
	Flooded	1.67 ± 0.07	1.71 ± 0.07
D	Voided	2.69 ± 0.11	2.66 ± 0.11
	Flooded	1.62 ± 0.07	1.65 ± 0.07

7 ROD 7%

B	Voided	4.92 ± 0.20	4.93 ± 0.20
	Flooded	2.77 ± 0.11	2.96 ± 0.12
C	Voided	4.56 ± 0.18	4.70 ± 0.19
	Flooded	2.61 ± 0.10	2.95 ± 0.12
D	Voided	4.43 ± 0.18	4.07 ± 0.16
	Flooded	2.47 ± 0.10	2.67 ± 0.11

6 ROD 3.5%

B	Voided	2.52 ± 0.10
	Flooded	1.48 ± 0.06
C	Voided	2.55 ± 0.10
	Flooded	1.50 ± 0.06
D	Voided	2.54 ± 0.10
	Flooded	1.49 ± 0.06

6 ROD 7%

B	Voided	3.95 ± 0.16
	Flooded	2.48 ± 0.10
C	Voided	4.10 ± 0.16
	Flooded	2.33 ± 0.09
D	Voided	3.96 ± 0.16
	Flooded	2.44 ± 0.10

Figure 32 - Relative U-238 Activation in 7 Rod 3.5% Enriched Lattices (43-025-254)

Figure 33 - Relative U-238 Activation in 7 Rod 7% Enriched Lattices (43-025-255)

Figure 34 - Relative U-238 Activation in 6 Rod 3.5% Enriched Lattices (43-025-256)

Figure 35 - Relative U-238 Activation in 6 Rod 7% Enriched (43-025-257)

REFERENCES

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