Consolidated Fuel Reprocessing Program

**Summary of Experimental
Data for Critical Arrays of
Water Moderated Fast Test
Reactor Fuel**

May 1981

**Prepared for
the Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830
under Purchase Order 97731**

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**the U.S. Department of Energy
Richland, Washington 99352
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SUMMARY OF EXPERIMENTAL DATA FOR
CRITICAL ARRAYS OF WATER MODERATED
FAST TEST REACTOR FUEL

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NOTICE This document contains information of a preliminary nature.
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SUMMARY

A research program, funded by the Consolidated Fuel Reprocessing Program (CFRP) of Oak Ridge National Laboratory (ORNL), was initiated at Battelle Pacific Northwest Laboratory (PNL) to acquire experimental data on heterogeneous water moderated arrays of Fast Test Reactor (FTR) fuel pins. The objective of this program is to provide critical experiment data for validating calculational techniques used in criticality assessments of reprocessing equipment containing FTR-type fuels. Consequently, the experiments were designed to permit accurate definition in Monte Carlo computer codes currently used in these assessments.

Square and triangular pitched lattices of fuel have been constructed under a variety of conditions covering the range from undermoderated to overmoderated arrays. Experiments were conducted composed of arrays which were water reflected, partially concrete reflected, and arrays with interspersed solid neutron absorbers. The absorbers utilized were Boral, and cadmium plates and gadolinium cylindrical rods.

Data from non-CFRP sponsored subcritical experiments (previously performed at Hanford) also are included in this report. In addition to the criticality data, included are measurements made with solid-state track recorders to characterize the fission rate distributions in several of the assemblies.

INTRODUCTION

A series of experiments has been performed at the PNL Critical Mass Laboratory on water flooded arrays of Fast Test Reactor (FTR) fuel pins in support of the Consolidated Fuel Reprocessing Program (CFRP) at ORNL. The fuel consists of mixtures of plutonium and natural uranium oxides ranging from ~20 to 25 wt% plutonium in the mixed oxide. The objective in these experiments was to provide reliable experimental data that could be used to benchmark computer codes and calculational techniques commonly used in criticality analyses of such systems. The data cover a wide range of water moderation, covering undermoderated to overmoderated systems with respect to minimum critical mass (water-to-fuel volume ratios of 31 to 1.67).

This report summarizes the results of the experiments performed at Hanford Utilizing FTR fuels in water; in particular, Fast Flux Test Facility (FFTF) fuels. Included in these measurements are the following:

- (1) Subcritical experiments with water flooded and reflected arrays of FTR-type fuel pins; performed in 1969.
- (2) critical experiments with water flooded and reflected arrays of FFTF-type fuel pins; performed during February, 1978.
- (3) critical experiments with water flooded and concrete reflected arrays of FFTF-type fuel pins; performed September, 1978.

- (4) critical experiments with water flooded and reflected arrays of FFTF-type fuel pins admixed with solid neutron absorbers; performed November, 1978 through January, 1979.
- (5) solid-state track recorder measurements to measure fission rate distributions.

Most of the experimental data presented has been published previously in the open literature. It is summarized in this document to better facilitate its use. Many of the experiment-calculation correlations have not been formally presented in report form before. However, these presented correlations are not intended to serve as a formal validation; they are included to provide the reader with some idea of what accuracies are obtainable with standard computational methods.

Pertinent descriptions are given of the experiments including simplified drawings describing the apparatus and compositions of all experimental components. Where calculations have been performed to compare with the experimental results, these comparisons are included along with a description of cross-section sets and computer models used. Although the majority of the data presented relate to the critical size of array of fuel rods, some data were acquired using solid-state track recorders, characterizing the spatial fission rate distributions in these arrays (see Appendix A).

SECTION I.

Subcritical Experiments with Water Flooded and Reflected Arrays of FTR-Type Fuel Pins

Description

A series of exponential and critical approach experiments were performed with FTR fuel pins⁽¹⁾ (the term, FTR, is used to denote any pin geometry containing FFTF-type mixed oxide). These particular experiments were performed using non-FTTF hardware containing prototype driver FFTF fuel pellets. These experiments were sponsored prior to CFRP experimentation and provide useful data on material buckling, relaxation length, and extrapolation distance. These data were obtained for 22.2 wt% Pu in plutonium and natural uranium oxide fuel pins in water. Fuel rods were loaded in a circular pattern on a triangular pitch. A water tank, 120 cm diameter by 183 cm high, allowed the water reflection and moderation of the fuel pin arrays. Plexiglas templates, 13 mm thick, held the fuel rods. The pitches vary from 11.4 to 34.3 mm. A description of the fuel is given in Figure 1.

Experimental Results

The critical number of fuel rods were determined from neutron multiplication measurements. Material bucklings and extrapolation distances were in turn obtained by using data from exponential pile measurements on subcritical assemblies.

Fuel Pin Dimensions (mm)			
	i.d.	o.d.	Length
Fuel Column	----	4.95	692.2
Cladding (Type 316 Stainless Steel)	5.13	5.84	729.0
Lower Endcap	----	----	3.56
Upper End Spacer	----	----	6.35
Upper Air Gap	----	----	17.72
Upper Endcap	----	----	5.64
Heavy Metal Composition (wt%): Plutonium 25.2			
Uranium 74.8			

Fuel Per Pin	
PuO ₂ -U(Nat)O ₂ :	138.4 ± 1.23 g
Pu:	30.75 ± 0.03 g
U:	91.16 ± 1.03 g
O:	16.49 ± 0.17 g

Fuel Density
10.35 ± 0.09 g/cm ³
(93.34 ± 0.79% theoretical)

Isotopic Composition of Plutonium in Pins (Wt%)		
²³⁸ Pu:	0.04 ± 0.01	0.04 ± 0.01
²³⁹ Pu:	86.19 ± 0.06	86.14 ± 0.06
²⁴⁰ Pu:	11.88 ± 0.06	11.92 ± 0.06
²⁴¹ Pu:	1.73 ± 0.01	1.74 ± 0.01
²⁴² Pu:	0.16 ± 0.01	0.16 ± 0.01

Figure 1. FTR Fuel Pin Description

The experimental results, shown in Table I, indicate a minimum number of 150 rods for criticality at a triangular pitch of ~ 23 mm. It is estimated that the error in the critical number of rods determined per experiment is $\leq 2.5\%$.

TABLE I

Results of Critical Approach and Exponential Experiments
With 22.2 Wt% Pu Pins in Water

Lattice Pitch (mm)	Water to-Fuel Volume Ratio	Critical Approach Experiments		Exponential Experiments		Material Buckling (m ⁻²)	Extrapolation Distance ^{b)} (mm)
		Number of Pins for Criticality ^{a)}	Critical Mass (kg Pu)	Number of Pins in Assembly	Relaxation Length (mm)		
9	11.43	417 ± 5	12.8	222	145.9		
				270	192.8	153.8 ± 2.7	80.1
	15.24	219.2 ± 0.6	6.74	120	137.1	172.7 ± 2.2	72.5
	19.79	156.2 ± 0.8	4.80	78	127.2		
				90	150.5	160.9 ± 1.0	68.9
	22.86	149.8 ± 0.6	4.61	66	121.0		
				78	142.7	138.5 ± 1.0	89.0
	26.39	165.0 ± 0.2	5.07	84	153.7	111.6 ± 0.3	66.1
	30.48	232.6 ± 0.1	7.15	120	196.7	77.0 ± 1.0	61.1
	34.29	410 ± 10	12.6	---	---	~ 46.8	----

a) Obtained from least-squares fit of inverse multiplication measurements.
 All loadings were ≤ 96% of the predicted critical value.

b) Extrapolation distances are within ± 2.5 mm.

SECTION II.

Critical Experiments with Water Flooded and Reflected Arrays of FFTF-Type Fuel Pins

Description

The experiments in this section were performed with actual FFTF fuel pins loaned to PNL and CFRP. These pins were immersed in water and arranged in square lattices to obtain water-to-fuel volume ratios ranging from 17.53 to 1.67.⁽²⁾ These correspond to square lattice pitches of about 19.0 mm to 7.7 mm. A partially loaded lattice is shown in Figure 2.

Two types of FFTF fuel pins (characterized by different plutonium loadings in the fuel) were available for use in the critical experiments. These are identified as Type 3.1 (201 fuel pins) and Type 3.2 (999 fuel pins). Physically, both type fuel pins are similar. The common dimensions and those dimensions which differ between the two types of pins are shown in Figure 3. Both types of fuel pins are 5.842 mm in diameter and approximately 2.4 m in length. In either pin, the actual fuel region is restricted to a 914 mm length near the bottom of the pin. The remainder of the pin consists of end caps and other hardware.

Figure 2. Partially Loaded Lattice of FFTF Fuel Pins
Immersed in Water

SIMPLIFIED DESCRIPTION OF FAST TEST REACTOR FUEL PIN

- (a) Referenced Division of Reactor Development and Technology Standard
- (b) ²⁴¹Am content of Total Plutonium was Measured to be 0.13 Wt% during April and May of 1972.
- (c) 35.6 mm for Type 3.1 Fuel Pins

Figure 3. Simplified Description of FFTF Fuel Pin

The primary difference between the two types of fuel pins is the composition of the plutonium/uranium ratios in the fuel mixtures. The Type 3.1 fuel pins contain 24.39 Wt% Pu in the mixed oxide and the Type 3.2 contain 19.84 Wt% Pu. A complete composition breakdown of each type fuel mixture is given in Figure 3. The Am-241 content should be decay corrected to February, 1978. The plutonium in both pin types consists of 11.5 Wt% ^{240}Pu plutonium. The natural uranium isotopic distribution characterizes both Type 3.1 and Type 3.2 fuel pins.

The fuel region of each lattice was water flooded and reflected on all sides by at least 150 mm of water. However, the fuel pins were immersed in water only to a depth of 150 mm above the fuel region as indicated in Figure 4. Consequently the water reflector above the fuel zone was perforated by the FFTF fuel pin hardware. Deionized water (500,000 ohm minimum) was used in the experiments.

In all but one lattice, the grid plates used to obtain the desired spacings between the pins were of "eggcrate" type construction (welded steel [Type 304L] bars). In each lattice, these steel grids were located above and below the fuel region to minimize their reactivity effect on the experimental assembly. A photograph showing one set of steel grid plates mounted in position is shown in Figure 5. The fuel region of a FFTF fuel pin inserted in this assembly was between the bottom two grid plates.

(a) ELEVATIONS FOR TYPE 3.2 FUEL PINS. ELEVATIONS FOR TYPE 3.1 FUEL PINS ARE 5 mm LESS

(b) LOCATED OUTSIDE THE FUEL PIN ARRAY. NOT INVOLVED IN CRITICAL EXPERIMENTS

Figure 4. Relative Elevations - Critical Experiments with FFTF Fuel Pins in Water

Figure 5. Typical Set of Grid Plates

To prevent fuel pin deflections over this region, a spacer grid of polypropylene was provided in the fuel region of each lattice as indicated in Figure 4.

Each experimental assembly was provided with a Boral safety blade and a Boral control blade. However, these were fully withdrawn from each assembly during data acquisition. Although controlled criticality is normally achieved by movement of a control device, this perturbation was avoided in the measurements. The critical condition for each assembly was obtained by extrapolation of subcritical data to the critical condition. For this extrapolation, each experimental assembly was generally taken to within 1% of the critical symmetrical loading by observing the increase in neutron flux as fuel pins were symmetrically added to each assembly. Whenever 99% of the critical mass was not achieved with a symmetrical loading, the assembly was loaded to a critical condition for the control blade partially withdrawn to verify that the extrapolated critical condition was reasonable. Because of the neutron source indigenous to fuel of this type, no external source was used in any of the experiments.

Experimental Results

The data are summarized in Table II. The critical number of rods varied from a maximum of 1037 at a 7.671 mm pitch to 162 at a 19.05 mm pitch. Except for the 7.671 mm lattice, the critical assemblies in Table II contain only the Type 3.2 fuel pins in uniformly spaced arrays. At the 7.671 mm center-to-center pitch, the number of fuel pins required for criticality for a uniform array exceeded the available fuel pin

TABLE II

EXPERIMENTAL CRITICALITY DATA WATER FLOODED
TYPE 3.2 FTR FUEL PINS

EXPERIMENT REFERENCE NUMBER	SQUARE LATTICE PITCH ^(a) (mm)	WATER-TO-FUEL (VOL.RATIO)	LATTICE WIDTH (FUEL PINS)	CRITICAL NUMBER OF FUEL PINS ^(a)
003 R	7.671 ± 0.127	1.67	36	1037 ± 1 ^(b)
005	9.525 ± 0.127	3.33	28	605 ± 1
029 ^(c)	9.677 ± 0.127	3.49	28	579 ± 1
030 ^(d)	9.677 ± 0.127	3.49	28	579 ± 1
001	12.588 ± 0.127	6.87	18	279 ± 1
004	15.342 ± 0.127	10.88	18	205 ± 1
006	19.050 ± 0.127	17.53	14	162 ± 1

(a) ERROR LIMITS SHOWN ARE STANDARD DEVIATIONS AND ARE FOR THE INDICATED MEASURED PARAMETER ONLY

(b) INCLUDES 65 TYPE 3.1 FTR FUEL PINS ON A 15.342 mm LATTICE PITCH POSITIONED ON EITHER SIDE (36 ON ONE SIDE AND 29 ON THE OTHER) OF A 27 x 36 FUEL PIN ARRAY OF TYPE 3.2 FTR FUEL PINS AT A 7.671 mm SQUARE LATTICE PITCH

(c) STAINLESS (304L) STEEL LATTICE GRIDS REPLACED WITH 13.68 ± 0.04 mm THICK POLYPROPYLENE GRIDS

(d) SAME AS EXPERIMENT 029 EXCEPT DIFFERENT FUEL PINS OF THE SAME TYPE

inventory for these measurements. Normalized PNL calculations indicated that an assembly of only Type 3.2 fuel pins on a uniform 7.671 mm center-to-center spacing would require 1268 fuel pins to achieve criticality versus the 1200 FFTF fuel pins of both types available for these experiments. Consequently this lattice contains two pitches and 65 Type 3.1 fuel pins (see first entry of Table II). For this configuration, Type 3.1 fuel pins at a more reactive spacing of 15.342 mm were positioned on either side of a 36 x 27 array of Type 3.2 fuel pins (having the 7.671 mm center-to-center spacing). The fuel pin arrangement for this assembly is shown in Figure 6. Fuel arrangements for the other lattices are shown in Figures 7 through 11.

The data from these measurements are summarized in Figure 12 which shows the critical number of fuel pins as a function of lattice pitch. All of the assemblies were about 270 mm in width except for the 12.588 mm pitch assembly which was about 226 mm wide. Putting this assembly on a common 270 mm width basis, a buckling conversion was made which indicated that 294 pins would have been required for criticality. The figure shows that, at least for this particular array width, the pitch yielding the minimum number of rods for criticality had not yet been reached.

The steel grid plates were positioned to have a negligible effect on the criticality of the fuel pins in the assembly. Later experiments with grid plates constructed of polypropylene, and having a lattice spacing of 9.677 mm, confirmed this (see Figure 12).

(a) ELEVATIONS OF THE SOLID STATE TRACK RECORDER (SSTR) REFERENCE BARS ARE 1065.61 ± 1.52 mm AND 862.41 ± 1.59 mm ABOVE THE BOTTOM OF THE FUEL PINS FOR SSTRs NO. 1 AND 2 RESPECTIVELY. THE REFERENCE BAR FOR SSTRs NOS. 3, 4 AND 5 IS AT AN ELEVATION OF 659.21 ± 2.0 mm ABOVE THE BOTTOM OF THE FUEL PINS. SSTRs NOT IN ASSEMBLY DURING APPROACH TO CRITICAL

Figure 6. Layout of Critical Experiment No. 003R

FTR FUEL PINS OCCUPY SHADED LOCATIONS

Figure 7. Layout of Critical Experiment No. 001

(a) ELEVATIONS OF THE SOLID STATE TRACK RECORDER (SSTR) REFERENCE BARS ARE 1065.61 ± 1.52 mm AND 862.41 ± 1.59 mm ABOVE THE BOTTOM OF THE FUEL PINS FOR SSTRs NO. 1 AND 2 RESPECTIVELY. THE REFERENCE BAR FOR SSTRs NOS. 3, 4 AND 5 IS AT AN ELEVATION OF 659.21 ± 2.0 mm ABOVE THE BOTTOM OF THE FUEL PINS. SSTRs NOT IN ASSEMBLY DURING APPROACH TO CRITICAL

Figure 8. Layout of Critical Experiment No. 004

(a) ELEVATIONS OF THE SOLID STATE TRACK RECORDER (SSTR) REFERENCE BAR IS 1065.61 ± 1.52 mm ABOVE THE BOTTOM OF THE FUEL PINS FOR SSTR NO. 1. SSTR NOT IN ASSEMBLY DURING APPROACH TO CRITICAL

Figure 9. Layout of Critical Experiment No. 005

- (a) ELEVATIONS OF THE SOLID STATE TRACK RECORDER (SSTR) REFERENCE BARS ARE 1065.61 ± 1.52 mm AND 862.41 ± 1.59 mm ABOVE THE BOTTOM OF THE FUEL PINS FOR SSTRs NOS. 1 AND 2 RESPECTIVELY. THE REFERENCE BAR FOR SSTRs NOS. 3, 4 AND 5 IS AT AN ELEVATION OF 659.21 ± 2.0 mm ABOVE THE BOTTOM OF THE FUEL PINS. SSTRs NOT IN ASSEMBLY DURING APPROACH TO CRITICAL.

Figure 10. Layout of Critical Experiment No. 006

- (a) ELEVATIONS OF THE SOLID STATE TRACK RECORDER (SSTR) REFERENCE BARS ARE 1065.61 ± 1.52 mm AND 862.41 ± 1.59 mm ABOVE THE BOTTOM OF THE FUEL PINS FOR SSTRs NOS. 1 AND 2 RESPECTIVELY. THE REFERENCE BAR FOR SSTRs NOS. 3, 4 AND 5 IS AT AN ELEVATION OF 659.21 ± 2.0 mm ABOVE THE BOTTOM OF THE FUEL PINS.

Figure 11. Layout for Critical Experiment No. 029

Figure 12. Critical Rod Number versus Lattice Pitch for Rods in Water

The number of rods required for criticality increases with decreasing lattice pitch over the range examined. As indicated in Figure 12 and the data in Table II, a change of 0.15 mm in fuel pin spacing results in a 25 pin (4.3%) change in the number of fuel pins required for criticality in the vicinity of a 9.6 mm pitch. The same percent change in mass takes nearly 0.75 mm change in pitch in the vicinity of a 20 mm pitch.

Neutron Dosimetry Data

In order to acquire neutron dosimetry information on fission rates and distributions, solid state track recorders (SSTR) were inserted into some of the critical assemblies at various positions⁽³⁾ (see Appendix A). These recorders consist of deposits of fissionable material plated onto mica strips. When a fission occurs the fission fragments leave tracks in the mica which can be usually observed microscopically. Hence, a record is obtained of fission events, both spatially and spectrally.

The fissionable materials used in the foils were small deposits of ^{238}U , ^{237}Np , ^{239}Pu , ^{235}U and ^{232}Th . The foil holders perturbed the assemblies to a small degree while collecting the desired neutron spectra information. Hence the fuel pin loading patterns differed somewhat from the report critical configurations.

Correlation of Calculations with Experiments

Neutron multiplication factors (k_{eff}) were calculated by PNL for each of the critical assemblies using the KENO-IV computer code⁽⁴⁾ with ENDF/B data. Initially calculations were performed with cross-sections

obtained from FLANGE⁽⁵⁾ -ETOG⁽⁶⁾ processed ENDF/B-3 and ENDF/B-4 libraries. The THERMOS⁽⁷⁾ computer code was used to generate single group thermal data from its companion ENDF/B-3 library, and the EGGNIT⁽⁸⁾ code was used to generate seventeen group epithermal data from its ENDF/B-4 library. The results of these calculations are summarized in Table III.

Calculations with THERMOS-EGGNIT-ENDF/B data underestimate the critical size of each experimental assembly by 1 to 6% in k_{eff} . Because of these large differences between experiment and calculations, several possibilities were explored in an attempt to resolve the differences. For five of the lattices, k_{eff} calculations were made at loadings other than critical to establish the sensitivity of k_{eff} to errors in the experimentally determined number of fuel pins required for criticality. These results are also summarized in Table III and indicate that an error greater than 10% would have to exist in the critical size of each assembly to account for the differences observed between calculations and experiment. Since an error of this magnitude is inconceivable in these experiments, additional studies were carried out. The clad thickness was increased to the maximum tolerance of 0.0127 mm. Am-241 content was assumed to be twice the decay-corrected value. Different representatives of the lattices were used (in one case individual rods were modeled while in another instance cell-averaged cross-sections were used in a "smeared" pin model). The effect of all of the above changes, when considered separately, was within the statistical one sigma error bars shown for the calculations in Table III.

TABLE III

**SUMMARY OF CALCULATIONAL RESULTS
FTR FUEL PINS IN WATER**

EXPERIMENT NUMBER	SQUARE PITCH (mm)	LATTICE WIDTH (PINS)	TOTAL NUMBER OF PINS IN LATTICE (a)	INITIAL PNL $k_{eff}^{(b)}$ VALUES		CFRP INPUT RUN AT PNL
				EGGNIT-THERMOS/ KENO IV (c)	NITAWL / KENO IV (c)	
003 R	7.671	36 ^(d)	1037 ^(e)	1.010 ± 0.005	1.017 ± 0.005	0.986 ± 0.004
		36	1296	1.014 ± 0.004		
		36	1224	1.004 ± 0.004		
		36	1188	1.001 ± 0.004		
005	9.525	28	605 ^(e)	1.034 ± 0.005	1.016 ± 0.004	1.000 ± 0.004
029	9.677	28	579 ^(e)	1.035 ± 0.005	1.017 ± 0.005	1.009 ± 0.003
		28	605	1.043 ± 0.007		
		28	560	1.023 ± 0.005		
		28	504	1.006 ± 0.006		
001	12.588	18	279 ^(e)	1.038 ± 0.004	1.018 ± 0.004	1.002 ± 0.004
		18	306	1.066 ± 0.004		
		18	252	1.018 ± 0.005		
004	15.342	18	205 ^(e)	1.053 ± 0.005	1.014 ± 0.005	0.996 ± 0.004
		18	180	1.012 ± 0.006		
006	19.050	14	162 ^(e)	1.044 ± 0.004	1.012 ± 0.004	1.009 ± 0.004
		14	140	1.016 ± 0.005		
		14	112	0.946 ± 0.005		

(a) TYPE 3.2 FTR FUEL PINS UNLESS NOTED OTHERWISE

(b) ERROR LIMITS ARE ONE STANDARD DEVIATION ON THE KENO CALCULATIONS

(c) 18 ENERGY GROUP EGGNIT-THERMOS AVERAGED CROSS SECTIONS FROM FLANGE-ETOG PROCESSED ENDF/B-3 AND ENDF/B-4 DATA. ORNL 218 NEUTRON GROUP CRITICALITY LIBRARY COLLAPSED INTO 27 ENERGY GROUPS USING MALOCS MODULE IN AMPX

(d) 65 TYPE 3.1 FTR FUEL PINS ON A 15.342 mm LATTICE PITCH POSITIONED ON EITHER SIDE (36 ON ONE SIDE AND 29 ON THE OTHER) OF A 27 x 36 FUEL PIN ARRAY OF TYPE 3.2 PINS AT A 7.671 mm SQUARE PITCH

(e) EXPERIMENTALLY DETERMINED CRITICAL SIZE

(f) ORNL SCALE VERSION¹⁵ OF THE CRITICALITY SAFETY REFERENCE LIBRARY; DERIVED FROM ENDF/B-IV DATA USING A PRELIMINARY VERSION OF THE SCALE SYSTEM AND COLLAPSED INTO 27 GROUP FORM

The sensitivity of the calculations to the lattice pitch precision limits was also investigated. By referring to Figure 12, which gives the critical number of fuel pins as a function of lattice pitch, it can be seen that the measured variation of ± 0.127 mm in lattice pitch would not result in a significant change in the number of fuel pins required for criticality, except for the very undermoderated assembly.

Hence it was concluded that the differences between experiments and calculations were primarily due to errors in the EGGNIT code. Consequently a second set of KENO-IV calculations were performed with different cross-sections at both PNL and ORNL. The NITAWL module in the AMPX⁽⁹⁾ system was used to generate problem-dependent cross-sections with ENDF/B-4 data taken from the 218 neutron group ORNL Criticality Safety Reference Library (CSRL).⁽¹⁰⁾ The 218 group criticality library data was collapsed into a 27 broad-group structure, using the MALOCS module of AMPX. The results of the PNL calculations are shown in Table III and as observed, they are in much better agreement with the experiments than are the previous calculations with the THERMOS-EGGNIT data. The NITAWL-KENO-IV calculations underestimated the critical size of each assembly by only 1 to 2% in k_{eff} as compared to the 1 to 6% obtained in the initial calculations with THERMOS-EGGNIT data.

In order to compare AMPX versions at PNL with those used at ORNL, input from a CFRP representation was executed with PNL machines and codes. As can be seen the differences between these two calculations are negligible; hence it was tentatively concluded that there is not a significant

difference in the code versions and options used for this particular calculation between the two labs. For the PNL and CFRP NITAWL/KENO-IV representations, the observed non-statistical differences in k_{eff} can be attributed to input differences (additional CFRP calculational results using a third version of AMPX and KENO-IV for these experimental data are found in Table XVIII and also support this conclusion).

SECTION III.

Critical Experiments with Water Flooded and Concrete

Reflected Arrays of FFTF - Type Fuel Pins

Description

This Section details the results of experiments in which the water reflector surrounding the fuel rod arrays described in Section II was replaced by partial concrete reflection.⁽¹¹⁾ Polypropylene (0.904 gm/cm^3) grid templates were used to maintain uniform lattice spacings, replacing the steel mesh grids previously described. Some pitches, as a result, were slightly different from those used in the water reflected experiments. The center-to-center fuel spacings were 9.53, 12.63, 15.41 and 19.06 mm respectively. In this series only Type 3.2 fuel pins were used (see Figure 3).

A generalized layout of the concrete reflected experiments is shown in Figure 13, and a photograph of the concrete slabs is shown in Figure 14. The fuel zone was reflected on the four vertical sides by water and 406 mm of concrete. On one vertical side, a movable concrete wall was positioned with its location dependent on the critical length of the array. Reflection underneath the fuel zone was provided by water, the steel tank bottom, and a concrete floor (see Figure 15). Control and safety blade requirements necessitated a minimum water gap of about 20 mm between the concrete and the array boundaries. As indicated in Figure 15, the bottom of the fuel pins rested on the floor of the experimental vessel. The vessel was

VARIABLE DIMENSIONS, mm				
a	b	c	d	e
9.53 ± 0.13	20.22 ± 0.34	21.48 ± 0.87	20.22 ± 0.65	20.33 ± 0.24
12.63 ± 0.13	19.09 ± 0.18	15.94 ± 0.22	18.67 ± 0.65	18.78 ± 0.24
15.41 ± 0.13	32.00 ± 0.15	22.06 ± 0.24	17.28 ± 0.65	17.39 ± 0.24
19.06 ± 0.18	23.49 ± 0.47	21.48 ± 0.87	15.45 ± 0.65	15.56 ± 0.26

Figure 13. Diagrammatic Plan of Critical Experiment with Concrete Reflected FFTF Fuel Pins in Water

Figure 14. Concrete Reflectors Used in These Experiments

a carbon steel tank containing deionized water (500,000 ohm minimum) and sitting on a concrete floor at least 406 mm thick. The top of the fuel region was covered with at least 150 mm of water. (The hardware extending above and below the fuel region of each pin precluded vertical concrete reflection).

Critical approach type measurements were made for each lattice by observing the increase in neutron multiplication as fuel pins were added symmetrically to the system. During the initial loadings, the movable concrete block was away from the fuel. As the critical loading became evident, this piece of concrete was moved to the last row of fuel and the critical approach measurement completed.

Concrete Reflector

The concrete side reflectors were specifically fabricated with aggregates no larger than 38 mm for these experiments. At the time of fabrication, 150 mm diameter test samples were also poured. The density of these test samples was measured to be 2.416 g/cm^3 under room conditions. Immersed in water the concrete samples increased in weight, as shown in Figure 16, to an equilibrium density of 2.452 g/cm^3 . All of the experiments were performed with the concrete under this latter condition. A visual inspection of one of the samples, under equilibrium conditions, indicated a reasonably uniform distribution of moisture across the interior of the test sample.

The chemical composition of the concrete, based on the analysis of three samples, homogeneity, and the underwater equilibrium density, is

Figure 16. Water Absorption in Concrete Samples - Critical Experiments With Concrete Reflected FFTF Fuel Pins in Water

given in Table IV. The composition given in Table IV does not include the iron reinforcing bars shown in Figure 14 or the approximately same amount of iron contained in the lifting eye anchors located in the top face of each piece of concrete.

Experimental Results

The number of Type 3.2 FFTF fuel pins required for criticality is given for each lattice spacing in Table V. The Am-241 content of Figure 3 should be decay corrected to September 1978. As mentioned previously, the critical number of fuel pins was determined in each case by extrapolating subcritical neutron multiplication data to the critical condition as fuel pins were added symmetrically to the system. These lattices have a fixed width and are rectangular in shape. During the course of the experiments, fuel pin additions of half lattice widths were used to facilitate uniformity of neutron multiplication. That is for a lattice 18 fuel pins wide, each subcritical loading is limited to 9 fuel pins, or some multiple thereof, to achieve a correlation between loading increments that result in an accurate extrapolation to the critical condition.

By approaching the critical condition very closely an accurate extrapolation to criticality can be made. However, caution must be exercised when describing such a system for computer input. Consider, for example, experiment number 012 shown in Table V. At a square lattice pitch of 15.41 mm, 191 fuel pins would be required for criticality with a lattice 18 fuel pins wide.

TABLE IV

Composition of Concrete Reflector -
Critical Experiments - FTR Fuel Pins in Water

<u>Chemical Element</u>	<u>Wt% a)</u>
Al	2.32 $\pm$ 0.01
Ca	7.27 $\pm$ 0.28
Fe	0.28 $\pm$ 0.02
Si	34.68 $\pm$ 0.39
Mg	1.45 $\pm$ 0.05
K	0.75 $\pm$ 0.15
Na	0.17 $\pm$ 0.01
O	52.26 $\pm$ 0.58
H	0.82 $\pm$ 0.07

$\rho = 2.452 \text{ g/cm}^3$ equilibrium density, immersed in H_2O .

(a) Errors are 1σ standard deviations based on three analyses.

TABLE V

EXPERIMENTAL CRITICALITY DATA
CONCRETE REFLECTED TYPE 3.2 FTR FUEL PINS IN WATER

EXPERIMENT REFERENCE NUMBER	SQUARE LATTICE PITCH ^(a) (mm)	WATER-TO-FUEL (VOL. RATIO)	LATTICE WIDTH (FUEL PINS)	CRITICAL NUMBER OF FUEL PINS ^(a)	CRITICAL ROWS OF FUEL PINS ^(b)
010	9.53 ± 0.13	3.34	28	554 ± 1	19.79
007	12.64 ± 0.13	6.92	18	260 ± 1	14.44
012	15.41 ± 0.13	10.99	18	191 ± 1	10.61
011	19.06 ± 0.18	17.55	14	152 ± 1	10.86

(a) ERROR LIMITS SHOWN ARE STANDARD DEVIATIONS AND ARE FOR THE INDICATED MEASURED PARAMETER ONLY

(b) IN CALCULATIONS, THIS IS THE MORE CORRECT VALUE TO USE FOR THE CRITICAL CONDITION SINCE, IN RECTANGULAR LATTICES, THE REACTIVITY WORTH OF A FUEL PIN IS DEPENDENT ON ITS LOCATION IN A ROW OF FUEL PINS

To be exactly consistent with the critical extrapolation in computer calculations, the last partial row of fuel pins should be represented as a full row of fractional fuel cells as given in Table V. Experiment 012, for example, should be represented as 10 full rows composed of 18 complete fuel cells plus one full row of 18 fuel cells that are only 61% (9.41 mm) as thick as a normal fuel cell (15.4 mm).

The number of fuel pins required for criticality is plotted in Figure 17 as a function of the array pitch. Data from the previous measurements with full water reflection are also presented in Figure 17 for comparison. As can be seen, fuel assemblies reflected by concrete required 6 to 8% fewer fuel pins than did the corresponding assemblies with full water reflection.

Correlation of Calculations with Experiments

In order to check calculational methods, a series of calculations was performed at ORNL for a variety of models. The AMPX-II computer code system⁽¹⁶⁾ was used to model these benchmarks. Cross-sections were supplied from the standard 27 energy-group subset of the Criticality Safety Reference Library⁽¹²⁾ and processed by the NITAWL module in AMPX-II. These were input into the KENO-IV code.⁽¹⁷⁾ A complex geometric model was performed in KENO-KV as well as a simplified model, to show a comparison in reactivity of different models.

Rather than model each experiment as a number of whole rows in length plus fractional rows, each rod cell was modeled discretely (to the geometrical detail given in Figure 3), (see Table VI). Partial rows of fuel

Figure 17. Comparison of Full Water Reflected and Concrete Reflected FFTF Data

TABLE VI
K-effective for Various KENO-IV Models^(a)

	Pitch (10 ⁻³ m)	Critical Number of Pins	Lattice Width (Fuel Pins)	Calculated K-effective ^(b)					
				Position of Vacancies				Simplified Model With Water Gap	Simplified Model Without Water Gap
				Assymetric	Symetric				
					Outside	Inside	Alternating		
39	9.53	554	28	1.01912	1.02145	1.02330	1.01409	1.01382	1.03792
	12.64	260	18	1.01843	1.02579	1.02193	1.03146	1.02577	1.03571
	15.41	191	18	1.01685	1.02391	1.02456	1.02536	1.02181	1.04673
	19.06	152	14	1.02763	1.02323	1.02610	1.02505	1.02341	1.03596

(a) Calculated using the AMPX-II⁽¹⁶⁾ computer system to process 27 broad-group cross-sections⁽¹⁰⁾ in NITAWL for input into KENO IV.⁽¹⁷⁾ The individual rod cells were modeled discretely.

(b) 73,500 histories; 1 standard deviation $\leq$ 0.00300.

rods were then positioned at various locations to show sensitivity of the reactivity to the location of fuel rods. As can be seen in Table VI, the calculated reactivity may vary depending on where the fuel rods are placed; in one instance at a pitch of 12.64 mm, this difference amount to 12 mk (0.012 in k) if the partial row is modeled with all of the fuel rods to one side of the row or if in alternate hole locations. However, it should be noted that for a given experiment, all of the calculated k-effectives are within two standard deviations of each other. Hence statistics mask any effect due to this experimental uncertainty. The most experimentally consistant model would, however, still be to utilize cell averaged cross-sections and model the partial row of fuel with partial cells extending the full width of the core.

Since these calculated reactivities were on the order of 10 to 20 mk higher than that which was observed with water reflector alone, some calculations were performed at ORNL to evaluate system sensitivity to water gap between concrete and fuel. In these cases, the water gap which was present between the fuel cell boundary and the concrete wall was replaced by concrete. As in seen, the effect on reactivity of adding this additional layer of concrete is significant, amounting to as much as 25 mk. Thus, the high bias observed could, in part be due to variations in the water gap dimension beyond those stated in Figure 13.

SECTION IV.

Critical Experiments with Solid Neutron Absorbers and Water-Moderated FFTF Fuel Pins

Description

This final Section gives the results of experiments in which arrays of the same fuel described in Section II and III were intermixed with solid neutron absorbers.⁽¹³⁾ Again, only Type 3.2 fuel rods were used, (see Figure 3). The Figure 3 Am-241 content should be decay corrected to December 1978 (the experiments were conducted from November 1978 to January 1979).

The experiments were performed with FFTF fuel elements immersed in water and arranged in uniform square pitch arrays having water-to-fuel volume ratios of ~ 3.5 to 31, (hydrogen atom to fissile atom ratios of 58 to 473). With respect to the minimum critical mass, this covers the range from undermoderated to overmoderated; pitches ranging in size from 9.7 to 24.9 mm respectively.

The neutron absorbers utilized in these experiments were Boral and cadmium in the form of thin plates and gadolinium in the form of cylindrical rods. These absorbers are described in Figures 18 to 20.

A schematic of the experiment arrangement is shown in Figure 21. Four polypropylene lattice templates (density of 0.903 g/cm^3) were used to uniformly position the fuel pins. These templates were slotted above

Figure 18. Description of Cadmium Absorber Plates

Figure 19. Description of Boral Absorber Plates

Figure 20. Description of Gadolinium Poison Pin

Figure 21. Isometric View of Fuel and Absorber Plate Experiment Setup

the middle and edge fuel rows so that Boral and cadmium neutron absorber plates could be positioned in the fuel region along either the array edge or array center. Gd pins were loaded in place of fuel rods in similar positions, (see Figure 22).

The neutron absorbers extended above and below the fuel region, except for a 4 mm gap located near the center line of the fuel region for the Boral plates and a 29 mm gap for the cadmium plates. The Gd pins vertically spanned the entire fuel zone of the pin. Each absorber was separately examined to see its effect on system reactivity - none were intermixed.

The critical assemblies were reflected on all sides by at least 150 mm of deionized water. They were, however, immersed in water only to a height of 165 mm above the top of the fuel column. Consequently, the top reflector region above each fuel rod was perforated by fuel pin hardware projecting through the water.

Eight types of experiments were performed at lattice spacings of 9.68, 12.42, 15.37, 19.35 and 24.87 mm pitch respectively, covering under to overmoderated systems with respect to minimum critical mass. These included:

- (1) Experiments with no poisons added,
- (2) experiments with Boral, cadmium and gadolinium neutron absorbers placed in the array center row,

Figure 22. Loading of Gadolinium Pins into Assembly

- (3) experiments with the above poisons placed in the core edge row,
- (4) gadolinium pins centered in the middle of clusters of fuel rods across the fuel core.

Experimental Results

The experiment results are summarized in Tables VII - XI. A detailed geometric description of each is given in Appendix B. As was expected, the 9.68 mm array required the most rods for criticality of a square array for an unpoisoned system, requiring 572 rods, whereas the 19.35 mm lattice - pitch array required the least number, 165 rods. As these values depend on array width and length, buckling corrections were made to estimate the minimum critical number of rods for unpoisoned arrays. As shown in Figure 23, the minimum number of 157 rods occurs at a pitch of 20.5 mm, a water-to-fuel volume ratio of 20.5. This was done by calculating the material buckling using EGGNIT and calculating the extrapolation distance at the critical array width and length. This value was then used to determine the square array critical dimensions.

Figure 24 shows a relative comparison of the number of rods required for criticality for the different poisons at different lattice spacings. Though no attempt was made to account for buckling effects, some noticeable trends can be seen. In all instances, irrespective of water-to-fuel ratio, the Boral plate, centrally positioned is the most effective neutron absorber. Also, the Boral plate placed at the fuel core edge is a more efficient absorber of leakage neutrons than either the Cd plates

TABLE VII

CRITICAL ARRAY SIZE FOR 9.68 mm LATTICE FOR VARIOUS NEUTRON
ABSORBER POSITIONS IN FUEL ARRAY

EXPERIMENT NUMBER	NEUTRON ABSORBER ⁽⁴⁾ /	POSITION IN LATTICE ⁽¹⁾	ARRAY WIDTH (PINS)	CRITICAL LENGTH ⁽²⁾⁽⁵⁾ (PINS)	CRITICAL NUMBER OF FUEL PINS
21	NONE	/ ---	25	22.88	571.9
22	Cd	/ ROW 1 (EDGE)	24	27.12	650.8
23	BORAL	/ ROW 1 (EDGE)	24	27.77	666.6
26	Gd	/ ROW 1 (EDGE)	24	27.08	648.0
24	Cd	/ ROW 13 (MIDDLE)	24	29.80	715.2
25	BORAL	/ ROW 13 (MIDDLE)	24	37.32	895.7
27	Gd	/ ROW 13 (MIDDLE)	24	31.93	766.4
28	Gd	/ Gd PINS CENTERED IN 5x5 FUEL CLUSTERS ⁽³⁾	25	29.82	715.5

- (1) "ROW" REFERS TO LINE OF LATTICE HOLES RUNNING PARALLEL TO LONG SIDE OF TEMPLATES. (SEE FIGURE 21). THE "EDGE" ROW MEANS THE ROW OF TEMPLATE HOLES NORMALLY OCCUPIED BY THE FIRST ROW OF FUEL. THE MIDDLE ROW, LIKEWISE, REFERS TO THE ROW OF HOLES IN THE ARRAY CENTER.
- (2) THE CORRECT INTERPRETATION OF THE CRITICAL LENGTH IS TO ASSUME THIS AS A FRACTION OF A FULL CELL ALONG THE ENTIRE ARRAY WIDTH. FOR EXAMPLE, IF THE ARRAY LENGTH IS 22.88 ROWS, THIS IS 22 ROWS PLUS 0.88 ROWS. DO NOT EQUATE THIS WITH NUMBER OF PINS IN A ROW OR THE POSITION OF THESE PINS IN THE FRACTIONAL ROW.
- (3) A Gd PIN IS POSITIONED AT THE CENTRAL POSITION OF EVERY 5x5 CLUSTER OF FUEL. THE ENTIRE ARRAY, IN TURN, IS PUT TOGETHER IN A REPETITIVE MANNER, OF THESE 5x5 CELLS.
- (4) THE BORAL AND Cd PLATES STRETCHED TO THE EDGE OF THE FULL 508 mm TEMPLATE LENGTH. CONSEQUENTLY, SOME PORTION OF THE PLATE WAS OUT IN THE WATER REFLECTOR REGION. THE Gd PINS, HOWEVER, DID NOT EXTEND OUT INTO THE WATER BEYOND THE FUEL.
- (5) THE EXPERIMENT ERROR IS $\leq 0.5\%$ IN CRITICAL LENGTH

TABLE VIII

CRITICAL ARRAY SIZE FOR 12.42 mm LATTICE FOR VARIOUS NEUTRON
ABSORBER POSITIONS IN FUEL ARRAY

EXPERIMENT NUMBER	NEUTRON ABSORBER ⁽⁴⁾ / POSITION IN LATTICE ⁽¹⁾	ARRAY WIDTH (PINS)	CRITICAL LENGTH ⁽²⁾⁽⁵⁾ (PINS)	CRITICAL NUMBER OF FUEL PINS
43	NONE / ---	20	14.70	293.9
45	Cd / ROW 1 (EDGE)	19	16.49	313.3
46	BORAL / ROW 1 (EDGE)	19	16.91	321.2
44	Gd / ROW 1 (EDGE)	19	16.45	312.6
48	Cd / ROW 10 (MIDDLE)	18	21.87	393.6
49	BORAL / ROW 10 (MIDDLE)	18	27.01	486.1
47	Gd / ROW 10 (MIDDLE)	18	21.89	394.0
50	Gd / Gd PINS CENTERED IN 5x5 FUEL CLUSTERS ⁽³⁾	20	17.51	338.3

- (1) "ROW" REFERS TO LINE OF LATTICE HOLES RUNNING PARALLEL TO LONG SIDE OF TEMPLATES. (SEE FIGURE 21). THE "EDGE" ROW MEANS THE ROW OF TEMPLATE HOLES NORMALLY OCCUPIED BY THE FIRST ROW OF FUEL. THE MIDDLE, ROW, LIKEWISE, REFERS TO THE ROW OF HOLES IN THE ARRAY CENTER.
- (2) THE CORRECT INTERPRETATION OF THE CRITICAL LENGTH IS TO ASSUME THIS AS A FRACTION OF A FULL CELL ALONG THE ENTIRE ARRAY WIDTH. FOR EXAMPLE, IF THE ARRAY LENGTH IS 14.70 ROWS, THIS IS 14 ROWS PLUS 0.70 ROWS. DO NOT EQUATE THIS WITH NUMBER OF PINS IN A ROW, OR THE POSITION OF THESE PINS IN THE FRACTIONAL ROW.
- (3) A Gd PIN IS POSITIONED AT THE CENTRAL POSITION OF EVERY 5x5 CLUSTER OF FUEL. THE ENTIRE ARRAY, IN TURN, IS PUT TOGETHER IN A REPETITIOUS MANNER, OF THESE 5x5 CELLS.
- (4) THE BORAL AND Cd PLATES STRETCHED TO THE EDGE OF THE FULL 508 mm TEMPLATE LENGTH. CONSEQUENTLY, SOME PORTION OF THE PLATE WAS OUT IN THE WATER REFLECTOR REGION. THE Gd PINS, HOWEVER, DID NOT EXTEND OUT INTO THE WATER BEYOND THE FUEL.
- (5) THE EXPERIMENT ERROR IS $\leq 0.5\%$ IN CRITICAL LENGTH

TABLE IX

CRITICAL ARRAY SIZE FOR 15.37 mm LATTICE FOR VARIOUS NEUTRON
ABSORBER POSITIONS IN FUEL ARRAY

EXPERIMENT NUMBER	NEUTRON ABSORBER ⁽⁴⁾ /	POSITION IN LATTICE ⁽¹⁾	ARRAY WIDTH (PINS)	CRITICAL LENGTH ⁽²⁾⁽⁵⁾ (PINS)	CRITICAL NUMBER OF FUEL PINS
013	NONE	/ ---	15	13.11	196.7
014	Cd	/ ROW 1 (EDGE)	14	15.26	213.6
015	BORAL	/ ROW 1 (EDGE)	14	15.77	220.8
041	Gd	/ ROW 1 (EDGE)	14	15.22	213.1
016	Cd	/ ROW 8 (MIDDLE)	14	21.94	307.2
020	BORAL	/ ROW 8 (MIDDLE)	14	28.29	396.1
042	Gd	/ ROW 8 (MIDDLE)	14	20.91	292.7
040	Gd	/ Gd PINS CENTERED IN 5x5 FUEL CLUSTERS ⁽³⁾	15	15.94	230.1

- (1) "ROW" REFERS TO LINE OF LATTICE HOLES RUNNING PARALLEL TO LONG SIDE OF TEMPLATES. (SEE FIGURE 21). THE "EDGE" ROW MEANS THE ROW OF TEMPLATE HOLES NORMALLY OCCUPIED BY THE FIRST ROW OF FUEL. THE MIDDLE ROW, LIKEWISE, REFERS TO THE ROW OF HOLES IN THE ARRAY CENTER.
- (2) THE CORRECT INTERPRETATION OF THE CRITICAL LENGTH IS TO ASSUME THIS AS A FRACTION OF A FULL CELL ALONG THE ENTIRE ARRAY WIDTH. FOR EXAMPLE, IF THE ARRAY LENGTH IS 13.11 ROWS, THIS IS 13 ROWS PLUS 0.11 ROWS. DO NOT EQUATE THIS WITH NUMBER OF PINS IN A ROW, OR THE POSITION OF THESE PINS IN THE FRACTIONAL ROW.
- (3) A Gd PIN IS POSITIONED AT THE CENTRAL POSITION OF EVERY 5x5 CLUSTER OF FUEL. THE ENTIRE ARRAY, IN TURN, IS PUT TOGETHER IN A REPETITIOUS MANNER, OF THESE 5x5 CELLS.
- (4) THE BORAL AND Cd PLATES STRETCHED TO THE EDGE OF THE FULL 508 mm TEMPLATE LENGTH. CONSEQUENTLY, SOME PORTION OF THE PLATE WAS OUT IN THE WATER REFLECTOR REGION. THE Gd PINS, HOWEVER, DID NOT EXTEND OUT INTO THE WATER BEYOND THE FUEL.
- (5) THE EXPERIMENT ERROR IS $\leq 0.5\%$ IN CRITICAL LENGTH

TABLE X

CRITICAL ARRAY SIZE FOR 19.35 mm LATTICE FOR VARIOUS NEUTRON
ABSORBER POSITIONS IN FUEL ARRAY

EXPERIMENT NUMBER	NEUTRON ABSORBER ⁽⁴⁾ /	POSITION IN LATTICE ⁽¹⁾	ARRAY WIDTH (PINS)	CRITICAL LENGTH ⁽²⁾⁽⁵⁾ (PINS)	CRITICAL NUMBER OF FUEL PINS
32	NONE	/ ---	15	11.01	165.1
34	Cd	/ ROW 1 (EDGE)	14	12.15	170.1
35	BORAL	/ ROW 1 (EDGE)	14	12.30	172.2
33	Gd	/ ROW 1 (EDGE)	14	12.07	169.1
39	Cd	/ ROW 8 (MIDDLE)	14	19.07	267.0
38	BORAL	/ ROW 8 (MIDDLE)	14	23.00	322.0
37	Gd	/ ROW 8 (MIDDLE)	14	17.34	242.8
36	Gd	/ Gd PINS CENTERED IN 5x5 FUEL CLUSTERS ⁽³⁾	15	12.87	187.0

- (1) "ROW" REFERS TO LINE OF LATTICE HOLES RUNNING PARALLEL TO LONG SIDE OF TEMPLATES. (SEE FIGURE 21). THE "EDGE" ROW MEANS THE ROW OF TEMPLATE HOLES NORMALLY OCCUPIED BY THE FIRST ROW OF FUEL. THE MIDDLE ROW, LIKEWISE, REFERS TO THE ROW OF HOLES IN THE ARRAY CENTER.
- (2) THE CORRECT INTERPRETATION OF THE CRITICAL LENGTH IS TO ASSUME THIS AS A FRACTION OF A FULL CELL ALONG THE ENTIRE ARRAY WIDTH. FOR EXAMPLE, IF THE ARRAY LENGTH IS 11.01 ROWS, THIS IS 11 ROWS PLUS 0.01 ROWS. DO NOT EQUATE THIS WITH NUMBER OF PINS IN A ROW, OR THE POSITION OF THESE PINS IN THE FRACTIONAL ROW.
- (3) A Gd PIN IS POSITIONED AT THE CENTRAL POSITION OF EVERY 5x5 CLUSTER OF FUEL. THE ENTIRE ARRAY, IN TURN, IS PUT TOGETHER IN A REPETITIOUS MANNER, OF THESE 5x5 CELLS.
- (4) THE BORAL AND Cd PLATES STRETCHED TO THE EDGE OF THE FULL 508 mm TEMPLATE LENGTH. CONSEQUENTLY, SOME PORTION OF THE PLATE WAS OUT IN THE WATER REFLECTOR REGION. THE Gd PINS, HOWEVER, DID NOT EXTEND OUT INTO THE WATER BEYOND THE FUEL.
- (5) THE EXPERIMENT ERROR IS $\leq 0.5\%$ IN CRITICAL LENGTH.

TABLE XI

CRITICAL ARRAY SIZE FOR 24.87 mm LATTICE FOR VARIOUS NEUTRON
ABSORBER POSITIONS IN FUEL ARRAY

EXPERIMENT NUMBER	NEUTRON ABSORBER ⁽⁴⁾ / POSITION IN LATTICE ⁽¹⁾	ARRAY WIDTH (PINS)	CRITICAL LENGTH ⁽²⁾⁽⁵⁾ (PINS)	CRITICAL NUMBER OF FUEL PINS
51	NONE / ---	20	10.40	208.0
54	Cd / ROW 1 (EDGE)	18	11.10	199.8
55	BORAL / ROW 1 (EDGE)	18	11.17	201.0
53	Gd / ROW 1 (EDGE)	18	11.06	199.2
57	Cd / ROW 10 (MIDDLE)	18	17.31	311.5
58	BORAL / ROW 10 (MIDDLE)	18	18.89	340.0
56	Gd / ROW 10 (MIDDLE)	18	15.81	284.6
52	Gd / Gd PINS CENTERED IN 5x5 FUEL CLUSTERS ⁽³⁾	20	12.54	242.8

- (1) "ROW" REFERS TO LINE OF LATTICE HOLES RUNNING PARALLEL TO LONG SIDE OF TEMPLATES. (SEE FIGURE 21). THE "EDGE" ROW MEANS THE ROW OF TEMPLATE HOLES NORMALLY OCCUPIED BY THE FIRST ROW OF FUEL. THE MIDDLE ROW, LIKEWISE, REFERS TO THE ROW OF HOLES IN THE ARRAY CENTER.
- (2) THE CORRECT INTERPRETATION OF THE CRITICAL LENGTH IS TO ASSUME THIS AS A FRACTION OF A FULL CELL ALONG THE ENTIRE ARRAY WIDTH. FOR EXAMPLE, IF THE ARRAY LENGTH IS 10.40 ROWS, THIS IS 10 ROWS PLUS 0.40 ROWS. DO NOT EQUATE THIS WITH NUMBER OF PINS IN A ROW, OR THE POSITION OF THESE PINS IN THE FRACTIONAL ROW.
- (3) A Gd PIN IS POSITIONED AT THE CENTRAL POSITION OF EVERY 5x5 CLUSTER OF FUEL. THE ENTIRE ARRAY IN TURN, IS PUT TOGETHER IN A REPETITIOUS MANNER, OF THESE 5x5 CELLS.
- (4) THE BORAL AND Cd PLATES STRETCHED TO THE EDGE OF THE FULL 508 mm TEMPLATE LENGTH. CONSEQUENTLY, SOME PORTION OF THE PLATE WAS OUT IN THE WATER REFLECTOR REGION. THE Gd PINS, HOWEVER, DID NOT EXTEND OUT INTO THE WATER BEYOND THE FUEL.
- (5) THE EXPERIMENT ERROR IS $\leq 0.5\%$ IN CRITICAL LENGTH

Figure 23. Minimum Critical Number of Rods for Square Arrays as a Function of Square Pitch

Figure 24. Comparison of the Different Neutron Absorber Configurations Versus Cell Pitch

or the Gd poison pins. With reference to Table XII, however, there appear to be certain moderation ranges where one absorber is more effective than another. Boral, for example is most effective at a water-to-fuel ratio of about 11. Notice that with the Boral or cadmium on the array edge, the size of the Boral poisoned system to the size of the cadmium poisoned system changes very little with moderation, but there is a dramatic change with moderation for the poisons centrally positioned. A similar relationship is observed when comparing Cd to Gd. A further interesting result is that Gd pins on the array edge, were observed to have nearly an identical effect as cadmium plates on the array edge irrespective of degree of moderation.

As used in these experiments, Boral was the most effective neutron absorber. This was to be expected considering that all three absorbers exhibit self shielding. Considering the density of neutron absorber atoms and form of material, Gd should experience the most self-shielding with cadmium and Boral following suit. A similar behavior between Cd and Boral was observed in experiments performed by Bierman, et. al., ⁽¹⁴⁾ exploring the water separation between rod clusters of uranium oxide rods separated by neutron absorber sheets. In those experiments, decreasing the Cd thickness from 0.91 mm to 0.61 mm had very little effect on system reactivity. Another factor which adds to the decreased effectiveness in the Cd experiments is a much larger gap between the absorber plates in the central plane of the core, 4 mm for Boral and 29 mm for cadmium.

TABLE XII

RATIOS OF CRITICAL NUMBERS OF RODS FOR VARIOUS NEUTRON ABSORBERS

PITCH (mm)	VOLUME RATIO		<u>BORAL (EDGE)</u> Cd	<u>BORAL (CENTER)</u> Cd	<u>BORAL (EDGE)</u> Gd	<u>BORAL (CENTER)</u> Gd	<u>Cd (EDGE)</u> Gd	<u>Cd (CENTER)</u> Gd
	<u>WATER</u>	<u>FUEL</u>						
9.68	3.49		1.02	1.25	1.02	1.17	1.00	0.93
12.42	6.65		1.03	1.24	1.03	1.23	1.00	1.00
15.37	10.93		1.03	1.29	1.03	1.35	1.00	1.05
19.35	18.13		1.01	1.21	1.02	1.33	0.99	1.10
24.87	30.87		1.01	1.09	1.01	1.19	1.00	1.09

It is interesting to note there is a greater % change in critical mass for the most undermoderated arrays when adding Gd poison pins than when the array is near the point of optimum moderation with respect to minimum critical mass. This can be seen in Table XIII.

Correlation of Calculations with Experiments

The experiments were calculated with the AMPX-II⁽¹⁶⁾/KENO-IV⁽¹⁷⁾ codes by CFRP as shown in Tables XIV to XVIII. In Table XVIII two sets of calculations were performed for the 15.4 mm square lattice, one using an homogenized cell model (cell weighted cross sections) and one in which each pin cell was discretely modeled (used also in Tables XIV to XVII). For all calculations, the AMPX-II⁽¹⁶⁾ system and 27 broad-group CSRL library⁽¹⁰⁾ were used for cross-section input into KENO-IV.⁽¹⁷⁾

The agreement is quite good; again, pin placement of individual pins in the heterogeneous model is not significant except perhaps for the 24.87 mm pitch calculations. Instead a slight bias is observable (for both representations) and is characterized by underpredicting k-effective at the tighter pitches and overpredicting for the more thermalized systems (wider pitches). Similar trends can be seen in Tables III and VI. While this bias in calculated k-effectives using the homogenized representation (Table XVIII) is slightly worse than for the discrete calculations, the machine and setup time savings are perhaps more significant and favor the homogenized representation.

TABLE XIII

COMPARISON OF NUMBER OF RODS REQUIRED FOR CRITICALITY FOR UNPOISONED ARRAYS AND GD PINS CENTERED IN 5×5 FUEL CLUSTERS

PITCH (mm)	UNPOISONED CRITICAL NO.
	<u>Gd PIN IN 5x5 FUEL CLUSTER CRITICAL NO.</u>
9.68	0.80
12.42	0.87
15.37	0.85
19.35	0.88
24.87	0.86

TABLE XIV

**SOME CALCULATED MULTIPLICATION FACTORS FOR FFTF PIN ARRAYS
WITH INTERSPERSED BORAL PLATES (USING NITAWL¹⁶ PROCESSED 27 BROAD-
GROUP CSRL CROSS SECTIONS¹⁰ AND KENO-IV¹⁷)**

SQUARE PITCH (mm)	NUMBER OF TYPE 3.2 PINS USED IN THE CALCULATION	PIN LOCATION ^(a)	CALCULATED K-eff	$\pm\sigma$	NUMBER OF TYPE 3.2 PINS USED IN THE CALCULATION	PIN LOCATION ^(b)	CALCULATED K-eff	$\pm\sigma$
9.68	663	15= 4-18	0.99771	0.00280	891	3= 1-3	1.00132	0.00304
	663	15= 6-20	0.99416	0.00296	891	3= 12, 14-15	0.99800	0.00281
	→ 666 ^(c)	18= 4-21	0.99543	0.00223	→ 895	7= 1-7	0.99934	0.00179
	→ 666	18= 1-9, 16-24	0.99948	0.00285	900	12= 1-12	0.99302	0.00281
	670	22= 3-24	0.99542	0.00300	900	12= 7-12, 14-19	0.99703	0.00290
12.42	319	15= 1-15	0.99467	0.00303	483	15= 2-10, 12-17	0.99805	0.00307
	319	15= 1-15	0.99713	0.00322	483	15= 4-10, 12-19	0.99786	0.00317
	→ 321	17= 1-17	0.99839	0.00270	→ 486	18= FULL ROW	1.00054	0.00190
	→ 321	17= 1-9, 12-19	1.00129	0.00327	489	3= 2-4	1.00014	0.00301
	322	18= 1-18	1.00142	0.00279	489	3= 10, 12-13	0.99997	0.00298
15.37	219	9= 1-9	1.00191	0.00297	394	2= 1-2	0.99873	0.00314
	219	9= 4-12	1.00194	0.00343	394	2= 7, 9	1.00597	0.00284
	→ 221	11= 1-11	1.00528	0.00298	→ 396	4= 1-4	0.99811	0.00199
	221	11= 1-5, 9-14	1.00435	0.00284	398	6= 1-6	1.00187	0.00267
	222	12= 1-12	1.00139	0.00288	398	6= 5-7, 9-11	1.00774	0.00290
	224	14= FULL ROW	1.00408	0.00269	398	6= 3-13, S2 ^(d)	1.00234	0.00289
19.35	171	3= 1-3	1.00308	0.00290	320	12= 1-7, 9-13	1.00771	0.00279
	171	3= 6-8	1.00263	0.00296	320	12= 1-6, 10-15	1.00493	0.00283
	→ 172	4= 1-4	1.00427	0.00265	→ 322	14= FULL ROW	1.00428	0.00198
	173	5= 1-5	1.00594	0.00285	324	2= 1-2	1.00456	0.00283
	173	5= 6-10	1.00511	0.00296	324	2= 7, 9	1.00676	0.00300
	173	5= 4-12, S2	1.00570	0.00293				
24.87	200	2= 2-3	1.00339	0.00283	338	14= 2-10, 12-16	1.00587	0.00266
	200	2= 10-11	1.00410	0.00263	338	14= 4-10, 12-18	1.00360	0.00269
	→ 201	3= 2-4	1.00133	0.00262	→ 340	16= 2-10, 12-18	1.00513	0.00209
	202	4= 2-5	1.01380	0.00264	341	17= 2-10, 12-19	1.00581	0.00296
	202	4= 9-12	1.00903	0.00282	342	18= FULL ROW	1.01091	0.00297
	202	4= 4-16, S4 ^(d)	1.00746	0.00258				

(a) READ AS NUMBER OF PINS IN FRACTIONAL ROW = CELL LOCATION FOR ARRAYS WITH A BORAL PLATE ON ARRAY EDGE.

(b) READ AS NUMBER OF PINS IN FRACTIONAL ROW = CELL LOCATION FOR ARRAYS WITH A BORAL PLATE IN ARRAY MIDDLE.

(c) → INDICATES NUMBER CLOSEST TO REPORTED CRITICAL NUMBER.

(d) S2 OR S4: READ AS EVERY SECOND OR FOURTH CELL IN THE RANGE SHOWN.

TABLE XV

**SOME CALCULATED MULTIPLICATION FACTORS FOR FFTF PIN ARRAYS
WITH INTERSPERSED CADMIUM PLATES (USING NITAWL¹⁶ PROCESSED
27 BROAD-GROUP CSRL CROSS SECTIONS¹⁰ AND KENO-IV¹⁷)**

SQUARE PITCH (mm)	NUMBER OF TYPE 3, 2 PINS USED IN THE CALCULATION	PIN LOCATION ^(a)	CALCULATED K-eff	$\pm \sigma$	NUMBER OF TYPE 3, 2 PINS USED IN THE CALCULATION	PIN LOCATION ^(b)	CALCULATED K-eff	$\pm \sigma$
9.68	647	23= 1-23	0.99732	0.00287	710	14= 6-12, 14-20	0.99894	0.00252
	648	24= FULL ROW	0.99614	0.00267	710	14= 1-3, 5-11: S2 ^(d) , 15-21: S2, 23-25	0.99591	0.00244
	→ 651 ^(c)	3= 1-3	0.99702	0.00197	711	15= 5-12, 14-20	1.00393	0.00263
	655	7= 1-7	1.00376	0.00290	→ 715	19= 1-12, 14-20	0.99747	0.00194
	655	7= 18-24	0.99531	0.00297	719	23= 1-12, 14-24	0.99785	0.00282
					720	24= FULL ROW	1.00057	0.00280
12.42	311	7= 1-7	0.99315	0.00296	391	13= 2-9, 13-17	0.99736	0.00289
	311	7= 1-19: S3 ^(d)	0.99649	0.00325	391	13= 4-10, 12-17	1.00006	0.00257
	311	7= 13-19	0.99189	0.00327	393	15= 2-10, 12-17	1.00383	0.00216
	→ 313	9= 1-9	0.99312	0.00205	→ 394	16= 2-10, 12-18	1.00041	0.00294
	315	11= 1-11	0.99988	0.00295	396	18= FULL ROW	1.00228	0.00273
	315	11= 9-19	0.99467	0.00307				
15.37	212	2= 1-2	0.99761	0.00339	305	11= 3-7, 9-14	0.99981	0.00291
	212	2= 13-14	1.00286	0.00331	305	11= 1-7, 9-15: S2	0.99866	0.00277
	→ 214	4= 1-4	0.99912	0.00213	307	13= 1-7, 9-14	1.00672	0.00210
	216	6= 1-6	1.00261	0.00320				
	216	6= 9-14	0.99808	0.00284				
	216	6= 3-13: S2	1.00655	0.00305				
19.35	169	1= 1	1.00396	0.00294	265	13= 1-14	1.00359	0.00288
	169	1= 14	1.00367	0.00276	265	13= 1-6, 9-15	1.01125	0.00294
	→ 170	2= 1-2	1.00077	0.00206	→ 267	1= 1	1.00700	0.00202
	171	3= 1-3	1.00391	0.00298	269	3= 1-3	1.00485	0.00281
	171	3= 12-14	0.99694	0.00294	269	3= 5-7	1.00608	0.00271
24.87	198	0	1.00566	0.00261	310	4= 2-5	1.00174	0.00272
	199	1= 2	1.00440	0.00184	310	4= 7-10	1.00340	0.00280
	→ 200	2= 18-19	1.00584	0.00259	→ 312	6= 2-7	1.00391	0.00198
	201	3= 2-4	1.00773	0.00268	314	8= 2-9	1.00576	0.00256
	201	3= 17-19	1.00915	0.00263	314	8= 4-18: S2	1.00751	0.00277

(a) READ AS NUMBER OF PINS IN FRACTIONAL ROW = CELL LOCATION FOR ARRAYS WITH A CADMIUM PLATE ON ARRAY EDGE.

(b) READ AS NUMBER OF PINS IN FRACTIONAL ROW = CELL LOCATION FOR ARRAYS WITH A CADMIUM PLATE IN ARRAY MIDDLE.

(c) → INDICATES NUMBER CLOSEST TO REPORTED CRITICAL NUMBER.

(d) S2 OR S3: READ AS EVERY SECOND OR THIRD CELL IN THE RANGE SHOWN.

TABLE XVI

**SOME CALCULATED MULTIPLICATION FACTORS FOR FFTF PIN ARRAYS WITH
INTERSPERSED GADOLINIUM PINS (USING NITAWL¹⁶ PROCE
27 BROAD-GROUP CSRL CROSS SECTIONS¹⁰ AND KENO-IV¹⁷)**

SQUARE PITCH (mm)	NUMBER OF TYPE 3.2 PINS USED IN THE CALCULATION	PIN LOCATION ^(a)	CALCULATED K-eff	$\pm \sigma$	NUMBER OF TYPE 3.2 PINS USED IN THE CALCULATION	PIN LOCATION ^(b)	CALCULATED K-eff	$\pm \sigma$
9.68	647	23- 1-23 (27)	0.99563	0.00292	762	18- 1-18 (31)	1.00008	0.00295
	647	23- 2-24 (27)	0.99333	0.00287	762	18- 4-12, 14-22 (31)	1.00431	0.00253
	→ 650 ^(c)	2- 12, 14 (27)	0.99831	0.00208	762	18- 4-12, 14-22 (32)	0.99709	0.00287
	653	5- 20-24 (27)	0.99837	0.00281	→ 766	22- 1-22 (31)	0.99824	0.00200
	653	5- 11-15 (27)	0.99802	0.00249	770	2- 6-7 (32)	0.99544	0.00269
12.42	310	6- 1-6 (16)	1.00266	0.00316	391	13- 2-14 (21)	0.99735	0.00297
	310	6- 8-13 (16)	0.99274	0.00321	391	13- 5-10, *12-18 (21)	0.99760	0.00282
	→ 312	8- 1-8 (16)	0.99434	0.00204	393	15- 2-10, 12-17 (22)	0.99894	0.00291
	315	11- 1-11 (16)	1.00088	0.00310	→ 394	16- 2-17 (21)	1.00056	0.00199
	315	11- 5-15 (16)	0.99117	0.00307				
15.37	212	2- 1-2 (15)	0.99176	0.00284	291	11- 2-7, 9-13 (20)	1.00765	0.00297
	212	2- 7-8 (15)	1.00317	0.00259	291	11- 2-7, 9-13 (21)	0.99829	0.00289
	→ 213	3- 1-3 (15)	0.99871	0.00217	→ 293	13- 1-7, 9-14 (21)	1.00163	0.00195
	214	4- 1-4 (15)	1.00423	0.00312	295	1- 9 (21)	0.99883	0.00286
	214	4- 6-9 (15)	1.00273	0.00299				
19.35	168	0 (12)	1.00306	0.00282	241	3- 1-3 (17)	1.00099	0.00286
	→ 169	1- 1 (12)	1.00204	0.00224	241	3- 1-3 (18)	1.00345	0.00293
	170	2- 1-2 (12)	1.01079	0.00294	241	3- 7-9 (17)	0.99995	0.00307
	170	2- 7-8 (12)	1.00788	0.00289	→ 243	5- 1-5 (17)	1.00615	0.00209
	171	3- 7-9 (12)	1.00298	0.00293	244	6- 6-11 (17)	1.00603	0.00292
24.87	198	0 (11)	0.99999	0.00277	283	13- 3-10, 12-16 (16)	1.00185	0.00262
	→ 199	1- 2 (11)	1.00713	0.00187	285	15- 2-10, 12-17 (16)	1.00441	0.00191
	200	2- 2-3 (11)	1.00851	0.00254	→ 285	15- 2-10, 12-17 (15)	1.00183	0.00245
	200	2- 10-11 (11)	1.01009	0.00252	286	16- 3-10, 12-19 (16)	1.00781	0.00247
	200	2- 18-19 (11)	1.00520	0.00278	286	16- 3-10, 12-19 (15)	1.00861	0.00234

(a) READ AS NUMBER OF PINS IN FRACTIONAL ROW * CELL LOCATION FOR ARRAYS WITH GADOLINIUM PINS ON ARRAY EDGE (NUMBER OF GADOLINIUM PINS).

(b) READ AS NUMBER OF PINS IN FRACTIONAL ROW * CELL LOCATION FOR ARRAYS WITH GADOLINIUM PINS IN ARRAY MIDDLE (NUMBER OF GADOLINIUM PINS).

(c) → INDICATES NUMBER CLOSEST TO REPORTED CRITICAL NUMBER.

TABLE XVII

**SOME CALCULATED MULTIPLICATION FACTOR FOR FFTF PIN ARRAYS
WITH INTERSPERSED GADOLINIUM PINS (USING NITAWL¹⁶
PROCESSED 27 BROAD-GROUP CSRL CROSS SECTIONS¹⁰ AND
KENO-IV¹⁷)**

SQUARE PITCH (mm)	NUMBER OF TYPE 3.2 PINS USED IN THE CALCULATION	PIN LOCATION ^(a)	CALCULATED K-eff	$\pm \sigma$
9.68	711	16= 1-16 (30)	0.99944	0.00272
	711	16= 5-20 (30)	1.00058	0.00273
	→ 715 ^(b)	20= 1-20 (30)	1.00321	0.00194
	719	24= 1-24 (30)	0.99797	0.00262
	719	24= 1-12, 14-25 (30)	1.00327	0.00272
12.42	336	8= 1-8 (12)	0.99736	0.00319
	336	8= 7-14 (12)	1.00428	0.00291
	→ 338	10= 1-10 (12)	1.00067	0.00219
	340	12= 1-12 (12)	0.99868	0.00287
	340	12= 5-16 (12)	1.00111	0.00269
15.37	228	12= 1-12 (9)	0.99748	0.00295
	228	12= 3-14 (9)	0.99716	0.00298
	→ 230	14= 1-14 (9)	1.00657	0.00232
	232	1= 3(9)	1.00488	0.00262
	232	1= 10 (9)	1.00830	0.00301
19.35	186	12= 1-12 (6)	1.00298	0.00319
	186	12= 1-6, 10-15 (6)	1.00130	0.00308
	→ 187	13= 1-13 (6)	1.00868	0.00223
	188	14= 1-14 (6)	1.00365	0.00287
	188	14= 1-7, 9-15 (6)	1.01033	0.00288
24.87	241	9= 1-9 (8)	1.00327	0.00255
	241	9= 6-14 (8)	1.00256	0.00277
	→ 243	11= 1-11 (8)	1.00755	0.00191
	244	12= 1-12 (8)	1.01256	0.00265
	244	12= 5-16 (8)	1.01228	0.00266

(a) READ AS NUMBER OF PINS IN FRACTIONAL ROW = CELL LOCATION FOR ARRAYS WITH GADOLINIUM PINS IN 5 x 5 UNIT CELLS (NUMBER OF GADOLINIUM PINS).

(b) → INDICATES NUMBER CLOSEST TO REPORTED CRITICAL NUMBER.

TABLE XVIII

SOME CALCULATED MULTIPLICATION FACTORS FOR WATER MODERATED FFTF PIN ARRAYS WITHOUT NEUTRON POISONS

SQUARE PITCH (mm)	NUMBER OF FFTF FUEL PINS	PIN LOCATION ^(a) (IF APPLICABLE)	DISCRETE CALCULATED ^(b) K-eff	+ σ	IBM 3033 MACHINE TIME (MINUTES)	REDUCED CELL WIDTH (mm) (IF APPLICABLE)	HOMOGENIZED CALCULATED K-eff	+ σ	IBM 3033 MACHINE TIME (MINUTES)
7.671	1036	10+ 18-36; S2	0.99142	0.00269	14.97220	FULL CELLS	0.98790	0.00298	9.55050
	→ 1037 ^(d)	11+ 16-36; S2	0.99268	0.00189	34.66440	FULL CELLS	0.99080	0.00209	18.58450
	1038	12+ 14-36; S2	0.98757	0.00275	14.90230	FULL CELLS	0.99251	0.00303	9.54650
	1039	13+ 12-36; S2	0.99196	0.00280	14.82100				
9.525	604	16+ 13-28	0.99786	0.00340	12.74820	FULL CELLS	0.98888	0.00315	8.68533
	→ 605	17+ 12-28	0.99533	0.00194	29.39930	FULL CELLS	0.99140	0.00226	17.01216
	606	18+ 11-28	0.98768	0.00302	12.67770	FULL CELLS	0.99344	0.00318	8.63500
9.677	569	19+ 1-19	0.99770	0.00306	12.55130	7.35460	0.99374	0.00318	8.72967
	→ 572	22+ 1-22	0.99621	0.00200	29.02880	8.51580	0.99430	0.00220	16.89950
	575	25+ FULL ROW	0.99612	0.00276	12.51570	9.67700	0.99058	0.00318	8.76700
12.420	292					7.45200	0.99612	0.00318	9.52767
	293	13+ 1-13	0.98992	0.00348	12.04880				
	→ 294	14+ 1-14	0.99705	0.00216	28.26570	8.69400	0.99644	0.00228	18.84134
	295	15+ 1-15	0.99761	0.00312	12.02600				
12.588	296					9.93600	1.00278	0.00320	9.69383
	278	8+ 2-9	0.99078	0.00296	12.15880				
	278	8+ 2-4, 10-11, 17-19				FULL CELLS	0.98899	0.00315	9.84583
	→ 279	9+ 2-4, 10-12, 17-19	0.99277	0.00202	27.89200	FULL CELLS	0.99837	0.00228	19.36034
	279	9+ 2-10	1.00077	0.00324	12.08080				
	280	10+ 2-11	1.00218	0.00265	12.03670				
	280	10+ 2-4, 9-12, 17-19				FULL CELLS	0.99843	0.00322	9.79267
	281	12+ 2-12	1.00357	0.00307	12.00720				
15.342	204	6+ 1-6	0.99667	0.00349	12.55270	FULL CELLS	1.00218	0.00309	11.32620
	→ 205	7+ 1-7	1.00099	0.00205	29.26580	FULL CELLS	1.00057	0.00222	22.15230
	206	8+ 1-8	1.00025	0.00296	12.58900	FULL CELLS	1.00278	0.00301	11.31200
	195.7					0.71800	0.99996	0.00329	11.01200
15.370	196	1+ 1	0.99912	0.00322	12.67030				
	196	1+ 8	0.99675	0.00322	12.08800				
	→ 196.65					1.69080	1.00146	0.00291	21.39980
	197	2+ 1-2	0.99821	0.00195	29.59530				
	197	2+ 7-8	1.00086	0.00218	29.48230				
	197.7					2.76660	1.00561	0.00307	10.84250
	198	3+ 1-3	1.00058	0.00304	12.58470				
	198	3+ 7-9	0.99924	0.00312	12.57080				
19.050	161	7+ 1-7	0.99822	0.00251	13.78130	FULL CELLS	1.00899	0.00281	13.26670
	→ 162	8+ 1-8	1.00567	0.00201	31.9170	FULL CELLS	1.01105	0.00209	25.96930
	163	9+ 1-9	1.00889	0.00302	13.58970	FULL CELLS	1.01617	0.00296	13.18870
19.350	164	14+ 1-14	1.00053	0.00288	14.35730				
	164.3					18.44700	1.01627	0.00299	13.00380
	165	15+ FULL ROW	1.00635	0.00204	33.39300				
	→ 165.15					0.19360	1.00767	0.00206	25.71820
24.870	166					1.29000	1.01269	0.00278	13.21000
	166	1+ 8	1.00243	0.00306	14.21830				
	207	7+ 1-7	1.00137	0.00283	17.41880	8.70400	1.01944	0.00257	17.00880
	207	7+ 8-14	1.00834	0.00254	17.44220				
	→ 208	8+ 1-8	1.00375	0.00170	40.70760	9.94800	1.02171	0.00179	33.53570
	→ 208	8+ 7-14	1.01008	0.00273	17.31430				
	209	9+ 1-9	1.00020	0.00272	17.43300	11.19200	1.01877	0.00239	17.01580
	209	9+ 6-14	1.01079	0.00265	17.26470				

(a) READ AS NUMBER OF PINS IN FRACTIONAL ROW = CELL LOCATIONS

(b) CALCULATED USING NITAWL¹⁶ PROCESSED 27 BROAD GROUP CSRL CROSS SECTIONS¹⁰ WITH KENO-IV¹⁷(c) CALCULATED USING NITAWL AND XSDRNPW WEIGHTED 27 GROUP CSRL CROSS SECTIONS¹⁰ WITH KENO-IV¹⁷(d) → INDICATES CONFIGURATION CLOSEST TO REPORTED
CRITICAL CONFIGURATION

(e) S2: READ AS EVERY SECOND CELL IN THE RANGE SHOWN

SUMMARY AND CONCLUSIONS

We have presented the results of four experimental series which have been performed at the PNL Critical Mass Laboratory to obtain data for heterogeneous assemblies of Fast Test Reactor Fuel pins moderated by water. The objective of these experiments was to provide an initial, reliable, experimental data base to be used for benchmarking computer codes and calculational schemes commonly used in the criticality safety design of such systems.

As a result of this work, experimental data exist against which the accuracy of computational methods can be checked for several systems. Such systems include: heterogeneous arrays of fast reactor fuel elements moderated by water, reflected by water or concrete, or admixed with neutron poisons such as Boron, cadmium or gadolinium.

In surveying the data, the following significant findings were observed:

1. Critical approach measurements have been performed for a variety of arrays of FTR fuel pins moderated and reflected with water. The arrays range from undermoderated with respect to minimum critical mass to overmoderated. Experimental data for both triangular and square arrays exist. Weight fractions range from ~20 to 25 Wt% Pu in $(U + Pu)O_2$. In all instances, the minimum mass, ~157 fuel rods, occurs at a water-to-fuel volume ratio of about 20. This corresponds to a 22 mm triangular pitch or a 20 mm square pitch for the rods used in this study.

2. When the water reflector region is replaced on four of six sides by 406 mm of concrete the critical mass is reduced by 6 to 8%. The minimum critical mass is, hence, reduced to about 140 fuel rods. AMPX-II/KENO-IV k_{eff} calculations, performed using the concrete experiment array data, are higher than water reflected array calculations. Concrete reflected rod systems were $\sim 2\%$ high in terms of k_{eff} , while water reflected arrays were, in general, $< 1\%$ high. Since additional calculations show a marked increase in reactivity as the water gap between the concrete reflector and fuel pin array is reduced in width, part of this effect may be due to variations in the reported water gap width. However, there are other possible sources of error such as non-uniform water density in the concrete and errors in the cross-section data used to mathematically represent concrete reflection.
3. When fuel is intermixed with solid neutron absorbers, the critical mass is increased. The Boral plates used in this study proved to be more effective than cadmium plates or gadolinium poison pins. This was true for undermoderated as well as moderated systems, with poison positioned centrally or along the fuel core edge. As expected, the absorbers vary in effectiveness depending on the degree of moderation.
4. For the gadolinium rods and cadmium plates used in this series of experiments, there is a crossover point where one or the other poison becomes more effective. The gadolinium rods were more effective for systems having water-to-fuel volume ratios less than ~ 6.5 . Above this

moderation range, the cadmium plates was more effective in increasing the amount of additional fuel needed for criticality. When positioned along the core edge, the gadolinium rods and cadmium plates were of nearly equal effectiveness.

5. The ratio of fuel to gadolinium was held constant in some of the experiments with gadolinium pins. The gadolinium maintained its effectiveness as the water-to-fuel volume ratio decreased from 31 to 3.5 (hydrogen atom to fissile atom ratios of 473 to 58).
6. Calculations performed of water reflected critical experiment arrays in most instances showed a slight bias as a function of pitch. The most experimentally consistent way to represent the experiment data for computer calculation is to use cell averaged, homogenized, cross-section sets and to treat fractional fuel rows as "thinner" fuel cells. However, homogenized calculational results generated in this manner, while less expensive, were generally slightly worse than arbitrarily selecting pin locations and calculating the arrays discretely. Hence, while such placement is experimentally important, the calculational results quoted were not nearly as sensitive to pin placement. The pitch related bias is more significant.

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APPENDIX A

Neutron Flux Spatial and Spectral Mapping Using Solid State Track Recorders (SSTR)

APPENDIX A

Neutron Flux Spatial and Spectral Mapping

Using Solid State Track Recorders (SSTR)

During the course of this experiment program, a number of solid state track recorder dosimetry measurements were performed to gather data on neutron fission distributions and spectrum.^{(1),(2)} These data are summarized in this appendix.

The measurements are carried out using thin mica fission track recorders with isotopic deposits of ^{235}U , ^{238}U , ^{232}Th and ^{237}Np . Fissions in the deposit create damage tracks in the mica which can then be counted under an optical microscope after suitable etching.⁽²⁾ The track record characterizes the neutron flux both spatially and spectrally.

In order to obtain track densities as close as possible, it was necessary to adjust deposit thicknesses for the different fissile materials to the optimum range for manual scanning. Consequently, many of the runs for which data are not shown, were used to optimize fission material deposits and critical flux levels per irradiation. Only the optimum runs have been included herein.

Table A.1 gives approximate lattice size for all SSTR irradiations. Representative drawings of the experiment loadings are shown in Figures A.1 thru A.7. Data obtained are summarized in Tables A.II thru A.IX. All fissile SSTR material locations are given with respect to the center of the fuel pin arrays. The overall experimental error for these SSTR based absolute fission rate observations is roughly 3-5% (at the 1 σ level).

TABLE A.I

FUEL PIN CONFIGURATIONS

<u>Irradiation Designation</u>	<u>Pitch, cm</u>	<u>Approximate Fuel Pin Array Dimension^(a)</u>	
		<u>x</u>	<u>y</u>
CS2	0.77	36	28.8
CS6	1.90	14	11.4
CS7	1.263	18	14.4
CS8	0.953	28	19.8
CS9	1.541	18	11.6
CS10	1.537	15	13.5
CS11	1.537	14	22.5
CS12	1.537	14	22.5

(a) Only an approximate number of fuel pins in the x and y dimensions can be given, as incomplete rows exist in most instances.

LAYOUT OF AFRCP CRITICAL EXPERIMENT
EXPERIMENT NO. 003R
FTR FUEL PINS IMMERSED IN WATER

^(a) ELEVATIONS OF THE SOLID STATE TRACK RECORDER (SSTR) REFERENCE BARS ARE 1065.61 ± 1.52 mm AND 862.41 ± 1.59 mm ABOVE THE BOTTOM OF THE FUEL PINS FOR SSTRs NO. 1 AND 2 RESPECTIVELY. THE REFERENCE BAR FOR SSTRs NOS. 3, 4 AND 5 IS AT AN ELEVATION OF 659.21 ± 2.0 mm ABOVE THE BOTTOM OF THE FUEL PINS. SSTRs NOT IN ASSEMBLY DURING APPROACH TO CRITICAL.

Figure A.1. Positions of the SSTR Reference Bars during experiment CS2. During the SSTR exposure, pins were present in the 2, 14 & 2, 12 positions in addition to those shown. An elevation of 659.21 mm above the bottom of the fuel pins corresponds to $\sim$ midplane.

TABLE A.II

FINAL SSTR RESULTS FOR IRRADIATION CS2

		(x,y,z)	Tracks/cm ²	Fissions/ μ g	Fissions/(atom-sec)	
SSTR Designation	Location, cm.					
²³⁵ U	1A	+7, 0, 40.64	6.684×10^4	3381	3.665	-16
	2A	+7, 0, 20.32	1.116×10^5	8156	8.841	-16
	3A	+7, 0, 0	1.073×10^5	11120	1.205	-15
	4A	+7, -6.16, 0	2.511×10^5	11020	1.195	-15
	5A	+7, -12.31, 0	2.292×10^5	9461	1.026	-15
	1B	-7, 0, +40.64	1.213×10^5	1784	1.934	-16
	2B	-7, 0, +20.32	2.772×10^5	8781	9.519	-16
	3B	-7, 0, 0	2.996×10^5	11890	1.289	-15
	4B	-7, -6.16, 0	3.753×10^5	10990	1.191	-15
	5B	-7, -12.31, 0	3.155×10^5	8183	8.870	-16
	1C	-4.5, 0, +40.64	1.650×10^5	3400	3.686	-16
	2C	-4.5, 0, +20.32	3.965×10^5	8872	9.617	-16
	3C	-4.5, 0, 0	5.144×10^5	12280	1.331	-15
	4C	-4.5, -6.16, 0	6.113×10^5	11051	1.198	-15
	5C	-4.5, -12.31, 0	5.151×10^5	9022	9.780	-16
	1D	-2, 0, +40.64	2.467×10^5	3628	3.933	-16
	2D	-2, 0, +20.32	5.525×10^5	8549	9.267	-16
	3D	-2, 0, 0	7.223×10^5	11910	1.291	-15
	4D	-2, -6.16, 0	0.441×10^5	12110	1.313	-15
	5D	-2, -12.31, 0	8.953×10^5	0670	1.048	-15
²³² Th	1E	+1, 0, +40.64	4.197×10^4	10.05	1.076	-18
	2E	+1, 0, +20.32	1.031×10^5	24.66	2.639	-18
	3E	+1, 0, 0	1.408×10^5	33.74	3.609	-18
	4E	+1, -6.16, 0	1.285×10^5	30.78	3.293	-18
	5E	+1, -12.31, 0	9.674×10^4	23.17	2.479	-18
	1H	-9, 0, +40.64	3.576×10^4	8.562	9.161	-19
	2H	-9, 0, +20.32	8.934×10^4	21.39	2.289	-18
	3H	-9, 0, 0	1.251×10^5	29.95	3.205	-18
	4H	-9, -6.16, 0	1.133×10^5	27.13	2.902	-18
	5H	-9, -12.31, 0	8.540×10^4	20.50	2.194	-18
²³⁸ U	1F	+3, 0, +40.64	1.412×10^5	32.49	3.567	-18
	2F	+3, 0, +20.32	3.340×10^5	76.94	8.448	-18
	3F	+3, 0, 0	4.699×10^5	108.3	1.189	-17
	4F	+3, -6.16, 0	4.614×10^5	106.2	1.166	-17
	5F	+3, -12.31, 0	3.425×10^5	78.90	8.663	-18
	1I	+9, 0, +40.64	1.287×10^5	29.64	3.254	-18
	2I	+9, 0, +20.32	3.208×10^5	73.89	8.133	-18
	3I	+9, 0, 0	4.426×10^5	102.0	1.120	-17
	4I	+9, -6.16, 0	3.788×10^5	87.28	9.583	-18
	5I	+9, -12.31, 0	2.881×10^5	66.37	7.287	-18
²³⁷ Np	1G	+5, 0, +40.64	6.733×10^3	193.6	2.116	-17
	2G	+5, 0, +20.32	2.277×10^4	654.8	7.157	-17
	3G	+5, 0, 0	2.696×10^4	775.3	8.474	-17
	4G	+5, -6.16, 0	2.223×10^4	639.3	6.998	-17
	5G	+5, -12.31, 0	1.858×10^4	535.2	5.850	-17

LAYOUT OF AFRCP CRITICAL EXPERIMENT

EXPERIMENT NO. 006

FTR FUEL PINS IMMERSED IN WATER

(a) ELEVATIONS OF THE SOLID STATE TRACK RECORDER (SSTR) REFERENCE BARS ARE 1065.61 ± 1.52 mm AND 862.41 ± 1.59 mm ABOVE THE BOTTOM OF THE FUEL PINS FOR SSTRs NOS. 1 AND 2 RESPECTIVELY. THE REFERENCE BAR FOR SSTRs NOS. 3, 4 AND 5 IS AT AN ELEVATION OF 659.21 ± 2.0 mm ABOVE THE BOTTOM OF THE FUEL PINS. SSTRs NOT IN ASSEMBLY DURING APPROACH TO CRITICAL.

Figure A.2. Positions of the SSTR reference bars during experiment CS6. An elevation of 659.21 mm above the bottom of the fuel pins corresponds to midplane.

TABLE A.III
FINAL RESULTS FOR IRRADIATION CS6

	SSTR Designation	(x,y,z) Location, cm	Tracks/cm ²	Fissions/ug	Fissions/(atom-sec)	
²³⁵ U	1B	-7, 0, +40.64	2.687 x 10 ⁵	5535	5.783	-16
	2B	-7, 0, +20.32	4.612 x 10 ⁵	13510	1.464	-15
	3B	-7, 0, 0	5.290 x 10 ⁵	16760	1.817	-15
	4B	-7, -3.81, 0	6.585 x 10 ⁵	15720	1.704	-15
	5B	-7, -9.525, 0	6.009 x 10 ⁵	10530	1.141	-15
	1C	-4.5, 0, +40.64	1.266 x 10 ⁵	6402	6.940	-16
	4C	-4.5, -3.81, 0	1.878 x 10 ⁵	19440	2.107	-15
	5C	-4.5, -9.525, 0	3.248 x 10 ⁵	13420	1.455	-15
	1D	-2, 0, +40.64	9.483 x 10 ⁴	6927	7.509	-16
	4D	-2, -3.81, 0	1.179 x 10 ⁵	19800	2.146	-15
	5D	-2, -9.525, 0	3.267 x 10 ⁵	14330	1.407	-15
	1H	+7, 0, +40.64	2.033 x 10 ⁵	4548	4.930	-16
	2H	+7, 0, +20.32	3.674 x 10 ⁵	11180	1.212	-15
	3H	+7, 0, 0	3.788 x 10 ⁵	15030	1.629	-15
	4H	+7, -3.81, 0	5.217 x 10 ⁵	13530	1.467	-15
	5H	+7, -9.525, 0	5.645 x 10 ⁵	10210	1.107	-15
²³⁹ Pu	2C	-4.5, 0, +20.32	1.685 x 10 ⁵	24650	2.716	-15
	3C	-4.5, 0, 0	1.622 x 10 ⁴	26320	2.900	-15
	2D	-2, 0, +20.32	1.460 x 10 ⁴	25250	2.783	-15
	3D	-2, 0, 0	1.815 x 10 ⁴	31910	3.516	-15
²³² Th	1A	-9, 0, +40.64	3998	0.9574	1.024	-19
	2A	-9, 0, +20.32	9652	2.311	2.473	-19
	3A	-9, 0, 0	1.163 x 10 ⁴	2.786	2.981	-19
	4A	-9, -3.81, 0	1.176 x 10 ⁴	2.816	3.013	-19
	5A	-9, -9.525, 0	8011	1.918	2.052	-19
	1E	+1, 0, +40.64	4.773 x 10 ³	1.143	1.223	-19
	2E	+1, 0, +20.32	1.278 x 10 ⁴	3.060	3.274	-19
	3E	+1, 0, 0	1.575 x 10 ⁴	3.772	4.036	-19
	4E	+1, -3.81, 0	1.513 x 10 ⁴	3.623	3.877	-19
	5E	+1, -9.525, 0	1.078 x 10 ⁴	2.581	2.762	-19
²³⁸ U	1F	+7, 0, 40.64	1.678 x 10 ⁴	3.865	4.244	-19
	2F	+7, 0, 20.32	4.114 x 10 ⁴	9.477	1.041	-18
	3F	+7, 0, 0	5.653 x 10 ⁴	13.02	1.430	-18
	4F	+7, -3.81, 0	5.658 x 10 ⁴	13.03	1.431	-18
	5F	+7, -9.525, 0	4.94 x 10 ⁴	9.661	1.061	-18
	1I	+9, 0, +40.64	1.077 x 10 ⁴	2.481	2.724	-19
	2I	+9, 0, +20.32	2.588 x 10 ⁴	5.962	6.546	-19
	3I	+9, 0, 0	3.069 x 10 ⁴	7.070	7.763	-19
	4I	+9, -3.81, 0	3.097 x 10 ⁴	7.134	7.833	-19
	5I	+9, -9.525, 0	2.406 x 10 ⁴	5.543	6.086	-19
²³⁷ Np	1G	+5, 0, +40.64	1031	29.65	3.241	-18
	2G	+5, 0, +20.32	2337	67.21	7.346	-18
	3G	+5, 0, 0	3028	87.08	9.518	-18
	4G	+5, -3.81, 0	2721	78.25	8.553	-18
	5G	+5, -9.525, 0	2307	66.35	7.252	-18

**DIAGRAMATIC PLAN
CRITICAL EXPERIMENT WITH CONCRETE REFLECTED
FTR FUEL PINS IN WATER**

Irradiation	VARIABLE DIMENSIONS, mm				
	a	b	c	d	e
CS-8	9.53 ± 0.13	20.22 ± 0.34	21.48 ± 0.87	20.22 ± 0.65	20.33 ± 0.24
CS-7	12.63 ± 0.13	19.09 ± 0.18	15.94 ± 0.22	18.67 ± 0.65	18.78 ± 0.24
CS-9	15.41 ± 0.13	32.00 ± 0.15	22.06 ± 0.24	17.28 ± 0.65	17.39 ± 0.24

Figure A.3. General Layout of Concrete Experiments, Showing SSTR Locations. All SSTR Recorders were Centrally Positioned

TABLE A.IV

FINAL SSTR RESULTS FOR IRRADIATION CS7

<u>Isotope</u>	<u>SSTR Designation</u>	<u>(x,y,z) Location (cm)</u>	<u>Tracks/cm²</u>	<u>Fissions/Atom</u>
²³² Th	1A	-7.62, 0, +40.64	5.193×10^3	4.790×10^{-16}
	3A	-7.62, 0, 0	2.010×10^4	1.854×10^{-15}
	1C	-2.54, 0, +40.64	6.622×10^3	6.108×10^{-16}
	3C	-2.54, 0, 0	2.558×10^4	2.360×10^{-15}
	1E	+2.54, 0, +40.64	5.970×10^3	5.507×10^{-13}
	3E	+2.54, 0, 0	2.653×10^4	2.447×10^{-15}
²³⁸ U	1F	+5.08, 0, +40.64	1.767×10^4	1.609×10^{-15}
	3F	+5.08, 0, 0	7.912×10^4	7.206×10^{-15}
²³⁷ Np	1D	0, 0, +40.64	9.651×10^2	1.698×10^{-13}
	3D	0, 0, 0	1.064×10^3	1.920×10^{-13}
²³⁵ U	1G	+7.62, 0, +40.64	1.055×10^5	3.414×10^{-12}
	3G	+7.62, 0, 0	3.336×10^5	3.815×10^{-12}
²³⁹ Pu	1B	-5.08, 0, +40.64	2.678×10^3	1.696×10^{-12}

TABLE A.V

FINAL SSTR RESULTS FOR IRRADIATION CS8

<u>Isotope</u>	<u>SSTR Designation</u>	<u>(x,y,z) Location (cm)</u>	<u>Tracks/cm²</u>	<u>Fissions/Atom</u>
²³² Th	1A	-7.62, 0, +40.64	1.666×10^4	1.537×10^{-15}
	3A	-7.62, 0, 0	5.370×10^4	4.953×10^{-15}
	1C	-2.54, 0, +40.64	2.052×10^4	1.893×10^{-15}
	3C	-2.54, 0, 0	6.608×10^4	6.095×10^{-15}
	1E	+2.54, 0, +40.64	1.815×10^4	1.674×10^{-15}
	3E	+2.54, 0, 0	7.250×10^4	6.688×10^{-15}
²³⁸ U	1F	+5.08, 0, +40.64	6.169×10^4	5.618×10^{-15}
	3F	+5.08, 0, 0	2.392×10^5	2.179×10^{-14}
²³⁷ Np	1D	0, 0, +40.64	1.397×10^4	4.367×10^{-14}
	3D	0, 0, 0	4.815×10^4	1.514×10^{-13}
²³⁹ Pu	1B	-5.08, 0, +40.64	5.008×10^4	3.172×10^{-11}
	3B	-5.08, 0, 0	1.445×10^4	9.751×10^{-12}
	1G	+7.62, 0, +40.64	4.763×10^4	2.719×10^{-12}
	3G	-7.62, 0, 0	1.632×10^5	1.228×10^{-10}

TABLE A.VI
FINAL SSTR RESULTS FOR IRRADIATION CS9

<u>Isotope</u>	<u>SSTR Designation</u>	<u>(x,y,z) Location (cm)</u>	<u>Tracks/cm²</u>	<u>Fissions/Atom</u>
²³² Th	1A	-7.62, 0, +40.64	8.037×10^3	7.414×10^{-16}
	3A	-7.62, 0, 0	3.048×10^4	2.812×10^{-15}
	1C	-2.54, 0, +40.64	1.046×10^4	9.649×10^{-16}
	3C	-2.54, 0, 0	2.970×10^5	2.740×10^{-14}
	1E	+2.54, 0, +40.64	1.042×10^4	9.612×10^{-16}
	3E	+2.54, 0, 0	4.191×10^4	3.866×10^{-15}
²³⁸ U	1F	+5.08, 0, +40.64	3.470×10^4	3.160×10^{-15}
	3F	+5.08, 0, 0	1.258×10^5	1.146×10^{-14}
²³⁷ Np	1D	0, 0, +40.64	7.537×10^3	2.356×10^{-14}
	3D	0, 0, 0	2.868×10^4	9.020×10^{-14}
²³⁹ Pu	1B	-5.08, 0, +40.64	8.088×10^4	6.087×10^{-11}
	3B	-5.08, 0, 0	3.261×10^5	2.454×10^{-10}
	1G	+7.62, 0, +40.64	1.036×10^5	5.915×10^{-12}
	3G	+7.62, 0, 0	3.650×10^5	2.746×10^{-10}

RELATIVE ELEVATIONS - FOR EXPERIMENTS CS2-9

^(a) ELEVATIONS FOR TYPE 3.2 FUEL PINS. ELEVATIONS FOR TYPE 3.1 FUEL PINS ARE 5 mm LESS

^(b) LOCATED OUTSIDE THE FUEL PIN ARRAY. NOT INVOLVED IN CRITICAL EXPERIMENTS

Figure A.4. Elevations of the SSTR Reference Bars During Experiment CS2-9. Reference Bars 3, 4, and 5 were all at the midplane position which is 659.21 mm above the bottom of the pins.

PLAN VIEW OF SSTR CS-10 EXPERIMENT NO POISON PLATES LOADED

A.12

Figure A.5. Plan View of CS-10

TABLE A.VII
FINAL SSTR RESULTS FOR IRRADIATION CS10

<u>Isotope</u>	<u>SSTR Designation</u>	<u>(x,y,z) Location (cm)</u>	<u>Tracks/cm²</u>	<u>Fissions/Atom</u>
²³² Th	1A	-5.08, +0.769, 0	2.039×10^4	1.881×10^{-15}
	2A	-5.08, -2.306, 0	1.884×10^4	1.738×10^{-15}
	3A	-5.08, +3.843, 0	1.729×10^4	1.595×10^{-15}
	4A	-5.08, +8.454, 0	1.335×10^4	1.231×10^{-15}
	5A	-5.08, +9.991, 0	1.222×10^4	1.127×10^{-15}
	2B	-2.54, -2.306, 0	1.948×10^4	1.797×10^{-15}
	4B	-2.54, +8.454, 0	1.500×10^4	1.384×10^{-15}
	1E	+5.08, +0.769, 0	1.742×10^4	1.607×10^{-15}
	5E	+4.08, +9.991, 0	1.227×10^4	1.178×10^{-15}
²³⁸ U	1B	-2.54, +0.769, 0	7.422×10^4	6.759×10^{-15}
	3B	-2.54, +3.843, 0	7.172×10^4	6.532×10^{-15}
	2E	+5.08, -2.306, 0	6.16×10^4	5.614×10^{-15}
	3E	+5.08, +3.843, 0	6.226×10^4	5.671×10^{-15}
	4E	+5.08, +8.454, 0	5.171×10^4	4.710×10^{-15}
	5B	-2.54, +9.991, 0	4.284×10^4	3.902×10^{-15}
²³⁷ Np	1D	+2.54, +0.769, 0	5.05×10^2	9.115×10^{-14}
	2D	+2.54, -2.306, 0	1.123×10^3	1.975×10^{-13}
	3D	+2.54, +3.843, 0	1.324×10^4	4.139×10^{-14}
	4D	+2.54, +8.454, 0	9.832×10^3	3.092×10^{-14}
	5D	+2.54, +9.991, 0	1.002×10^4	2.476×10^{-14}
²³⁹ Pu	1C	0, +0.769, 0	1.597×10^5	1.201×10^{-10}
	2C	0, -2.306, 0	1.804×10^5	1.358×10^{-10}
	3C	0, +3.843, 0	1.636×10^5	1.231×10^{-10}
	4C	0, +8.454, 0	1.052×10^5	7.217×10^{-12}
	5C	0, +9.991, 0	1.318×10^5	7.525×10^{-12}

PLAN VIEW OF SSTR EXPERIMENT CS-11, 12 CADMIUM BLADE IN LATTICE CENTER

Figure A.6. Plan View of CS-11 and 12

TABLE A.VIII
FINAL SSTR RESULTS FOR IRRADIATION CS11

<u>Isotope</u>	<u>SSTR Designation</u>	<u>(x,y,z) Location (cm)</u>	<u>Tracks/cm²</u>	<u>Fissions/Atom</u>
²³² Th	1A	-5.08, +0.769, 0	6.775 x 10 ³	6.249 x 10 ⁻¹⁶
	2A	-5.08, -2.306, 0	7.298 x 10 ³	6.732 x 10 ⁻¹⁶
	3A	-5.08, +3.843, 0	7.390 x 10 ³	6.817 x 10 ⁻¹⁶
	4A	-5.08, +8.454, 0	7.053 x 10 ³	6.506 x 10 ⁻¹⁶
	5A	-5.08, +9.991, 0	5.690 x 10 ³	5.249 x 10 ⁻¹⁶
	2B	-2.54, -2.306, 0	6.463 x 10 ³	5.962 x 10 ⁻¹⁶
	4B	-2.54, +8.454, 0	7.307 x 10 ³	6.740 x 10 ⁻¹⁶
	1E	+5.08, +0.769, 0	6.637 x 10 ³	6.122 x 10 ⁻¹⁶
	5E	+5.08, +9.991, 0	5.653 x 10 ³	5.214 x 10 ⁻¹⁶
²³⁸ U	1B	-2.54, +0.769, 0	2.396 x 10 ⁴	2.182 x 10 ⁻¹⁶
	3B	-2.54, +3.843, 0	2.590 x 10 ⁴	2.359 x 10 ⁻¹⁵
	2E	+5.08, -2.306, 0	2.314 x 10 ⁴	2.107 x 10 ⁻¹⁵
	3E	+5.08, +3.843, 0	2.772 x 10 ⁴	2.525 x 10 ⁻¹⁵
	4E	+5.08, +8.454, 0	2.107 x 10 ⁴	1.919 x 10 ⁻¹⁵
	5B	-2.54, +9.991, 0	2.226 x 10 ⁴	2.027 x 10 ⁻¹⁵
²³⁷ Np	1D	+2.54, +0.769, 0	6.637 x 10 ³	1.722 x 10 ⁻¹³
	2D	+2.54, -2.306, 0	---	---
	3E	+2.54, +3.843, 0	6.356 x 10 ³	1.987 x 10 ⁻¹⁴
	4D	+2.54, +8.454, 0	5.234 x 10 ³	5.852 x 10 ⁻¹⁷
	5D	+2.54, +9.991, 0	5.042 x 10 ³	1.335 x 10 ⁻¹⁴
²³⁹ Pu	1C	0, +0.769, 0	---	---
	2C	0, -2.306, 0	6.992 x 10 ⁴	5.262 x 10 ⁻¹¹
	3C	0, +3.843, 0	6.562 x 10 ⁴	4.938 x 10 ⁻¹¹
	4C	0, +8.454, 0	5.622 x 10 ³	3.857 x 10 ⁻¹²
	5C	0, +9.991, 0	5.885 x 10 ⁴	3.360 x 10 ⁻¹²

TABLE A.IX

FINAL SSTR RESULTS FOR IRRADIATION CS12

<u>Isotope</u>	<u>SSTR Designation</u>	<u>(x,y,z) Location (cm)</u>	<u>Tracks/cm²</u>	<u>Fissions/Atom</u>
²³⁵ U	1A	-5.08, +0.769, 0	3.502×10^4	4.004×10^{-13}
	2A	-5.08, -2.306, 0	6.764×10^4	5.906×10^{-13}
	3A	-5.08, +3.843, 0	8.318×10^4	5.686×10^{-13}
	4A	-5.08, +8.454, 0	9.466×10^4	4.916×10^{-13}
	5A	-5.08, +9.991, 0	1.736×10^5	5.569×10^{-13}
	1B	-2.54, +0.769, 0	4.232×10^4	4.283×10^{-13}
	2B	-2.54, -2.306, 0	8.492×10^4	6.827×10^{-13}
	3B	-2.54, +3.843, 0	9.073×10^4	5.838×10^{-13}
	4B	-2.54, +8.454, 0	9.870×10^4	4.886×10^{-13}
	5B	-2.54, +9.991, 0	1.990×10^5	5.519×10^{-13}
	1C	0, +0.769, 0	5.283×10^4	4.922×10^{-13}
	2C	0, -2.306, 0	8.854×10^4	6.248×10^{-13}
	3C	0, +3.843, 0	1.114×10^5	6.729×10^{-13}
	4C	0, +8.454, 0	1.356×10^5	5.714×10^{-13}
	5C	0, +9.991, 0	2.286×10^5	6.140×10^{-13}

ELEVATION VIEW OF EXPERIMENT ASSEMBLY

Figure A.7. Elevation View of Experiments CS-10, 11 and 12

REFERENCES

- 1) J. H. Roberts, et. al., "SSTR Dosimetry for the Advanced Fuel Recycle R&D Program (NO-2)," Letter Report, Westinghouse Hanford Company, June 28, 1978.
- 2) F. H. Ruddy, et. al., "SSTR Dosimetry for the Advanced Fuel Recycle R&D Program (No. 3)," Letter Report, Westinghouse Hanford Company, October 4, 1979.

APPENDIX B

Detailed Description of Experiments Utilizing Mixtures of Solid Neutron Absorbers and FTR Fuel Pins

APPENDIX B

Detailed Description of Experiments Utilizing Mixtures of Solid Neutron Absorbers and FTR Fuel Pins

The following appendix gives a detailed description of these experiments. All data were obtained using neutron multiplication measurements. Figures B.1 thru B.3 and Tables B.I thru B.III detail experiments in which Gd poison pins were placed in the fuel arrays. The cylindrical gadolinium neutron absorbers were described in Figure 20 of the text. The critical approaches were performed so that no gadolinium pins would extend out into the water region surrounding the fuel array. Each drawing is a plan view of one of the polypropylene templates, for a particular type of experiment. Since eight different types of experiments were performed, eight drawings are displayed. Each drawing shows such dimensions as drilled out hole size, distance from hole edges to the edge of the polypropylene plate and so on. The dark line labeled "cell edge" is an imaginary line which marks the edge of a fuel pin in water cell. There were one of four items occupying template hole locations: (1) fuel pins, (2) Gd neutron absorber pins, (3) neutron absorber plate or (4) water (empty cell location). A fuel pin in water constitutes a "fuel cell." An empty location constitutes a "water cell." A gadolinium pin in water or a neutron absorber blade in water is a "neutron absorber" cell. The critical fuel dimensions of the core are labeled "j" and "c." In nearly every case the length "j" is expressed in terms of complete and fractional fuel rows required for criticality. Again, the most experimentally consistent way in which to model this fractional row is to assume it

is composed of cells, having a reduced width, extending across the row. The drawings stress this fact.

The remaining diagrams describe all other experiments performed. The elevations for all pertinent experiment parts are shown in both Figures 21 and B-9. Information on the cadmium and Boral plates are found in Figures 18 and 19.

Figure B.1. View of Experiments with Gadolinium Pins Loaded in Edge Row

TABLE B.1

PHYSICAL DATA FOR EXPERIMENTS WITH GADOLIMIUM PINS LOADED IN EDGE ROW

EXP NO	CELL LATTICE PITCH (mm)	NUMBER OF DRILLED LATTICE HOLES ALONG LENGTH	NUMBER OF DRILLED LATTICE HOLES ALONG WIDTH	UNDRILLED POLYPROPYLENE TEMPLATE OVERHANG IN LENGTH (mm) (MEASURED FROM CELL EDGE TO TEMPLATE EDGE)	UNDRILLED POLYPROPYLENE TEMPLATE OVERHANG IN WIDTH (mm) (MEASURED FROM CELL EDGE)	DRILLED TEMPLATE HOLE SIZE (mm)	POLYPROPYLENE TEMPLATE WIDTH (mm)
	a	b	c	d	e	f	g
26	9.68 ± 0.01	40	25	60.40	25.05	6.05 ± 0.10	292 ± 1
44	12.42 ± 0.01	30	20	67.70	21.85	6.02 ± 0.05	292 ± 1
41	15.37 ± 0.01	32	15	8.08	30.78	6.02 ± 0.08	292 ± 1
33	19.35 ± 0.02	25	15	12.12	0.92	6.02 ± 0.10	292 ± 1
53	24.87 ± 0.01	20	20	5.30	5.30	5.97 ± 0.08	508 ± 1

EXP NO	CELL LATTICE PITCH (mm)	AVERAGE TEMPLATE THICKNESS (OF ALL 4 TEMPLATES) (mm)	AVERAGE SLOT WIDTH (mm)	AVERAGE SLOT DEPTH (mm)	NUMBER OF FUEL ROD CELLS IN WIDTH	CRITICAL NUMBER OF FUEL ROD CELLS IN LENGTH
	a		h		i	j
26	9.68 ± 0.01	13.3 ± 0.2	---	---	24	27.09
44	12.42 ± 0.01	13.1 ± 0.3	---	---	19	16.45
41	15.37 ± 0.01	13.1 ± 0.2	---	---	14	15.22
33	19.35 ± 0.02	13.1 ± 0.3	---	---	14	12.07
53	24.87 ± 0.01	13.1 ± 0.3	---	---	18	11.06

Figure B.2. Plan View of Experiments with Gadolinium Pins Loaded in Middle Row

TABLE B.II

PHYSICAL DATA FOR EXPERIMENTS WITH GADOLINIUM PINS LOADED IN MIDDLE ROW

EXP NO	CELL LATTICE PITCH (mm)	NUMBER OF DRILLED LATTICE HOLES ALONG LENGTH	NUMBER OF DRILLED LATTICE HOLES ALONG WIDTH	UNDRILLED POLYPROPYLENE TEMPLATE OVERHANG IN LENGTH (mm) (MEASURED FROM CELL EDGE TO TEMPLATE EDGE)	UNDRILLED POLYPROPYLENE TEMPLATE OVERHANG IN WIDTH (mm) (MEASURED FROM CELL EDGE)	DRILLED TEMPLATE HOLE SIZE (mm)	POLYPROPYLENE TEMPLATE WIDTH (mm)
	a	b	c	d	e	f	g
27	9.68 ± 0.01	40	25	60.40	25.05	6.05 ± 0.10	292 ± 1
47	12.42 ± 0.01	30	20	67.70	21.85	6.02 ± 0.05	292 ± 1
42	15.37 ± 0.01	32	15	8.08	30.78	6.02 ± 0.08	292 ± 1
37	19.35 ± 0.02	25	15	12.12	0.92	6.02 ± 0.10	292 ± 1
56	24.87 ± 0.01	20	20	5.30	5.30	5.97 ± 0.08	508 ± 1

EXP NO	CELL LATTICE PITCH (mm)	AVERAGE TEMPLATE THICKNESS (OF ALL 4 TEMPLATES) (mm)	AVERAGE SLOT WIDTH (mm)	AVERAGE SLOT DEPTH (mm)	NUMBER OF FUEL ROD CELLS IN WIDTH	CRITICAL NUMBER OF FUEL ROD CELLS IN LENGTH
	a		h		i	j
27	9.68 ± 0.01	13.3 ± 0.2	---	---	24	31.93
47	12.42 ± 0.01	13.1 ± 0.3	---	---	18	21.89
42	19.35 ± 0.02	13.1 ± 0.2	---	---	14	20.91
37	19.35 ± 0.02	13.1 ± 0.3	---	---	14	17.34
56	24.87 ± 0.01	13.1 ± 0.3	---	---	18	15.81

Figure B.3. Plan View of Experiments with Gadolinium Pins in the Middle of 5 x 5 Clusters of Fuel Rods

TABLE B.III

**PHYSICAL DATA FOR EXPERIMENTS WITH GADOLINIUM PINS LOADED
IN THE MIDDLE OF 5×5 CLUSTERS OF FUEL RODS**

EXP NO	CELL LATTICE PITCH (mm)	NUMBER OF DRILLED LATTICE HOLES ALONG LENGTH	NUMBER OF DRILLED LATTICE HOLES ALONG WIDTH	UNDRILLED POLYPROPYLENE TEMPLATE OVERHANG IN LENGTH (mm) (MEASURED FROM CELL EDGE TO TEMPLATE EDGE)	UNDRILLED POLYPROPYLENE TEMPLATE OVERHANG IN WIDTH (mm) (MEASURED FROM CELL EDGE)	DRILLED TEMPLATE HOLE SIZE (mm)	POLYPROPYLENE TEMPLATE WIDTH (mm)
	a	b	c	d	e	f	g
28	9.68 ± 0.01	40	25	60.40	25.05	6.05 ± 0.10	292 ± 1
50	12.42 ± 0.01	30	20	67.70	21.85	6.02 ± 0.05	292 ± 1
40	15.37 ± 0.01	32	15	8.08	30.78	6.02 ± 0.08	292 ± 1
36	19.35 ± 0.02	25	15	12.12	0.92	6.02 ± 0.10	292 ± 1
52	24.87 ± 0.01	20	20	5.30	5.30	5.97 ± 0.08	508 ± 1

EXP NO	CELL LATTICE PITCH (mm)	AVERAGE TEMPLATE THICKNESS (OF ALL 4 TEMPLATES) (mm)	NUMBER OF FUEL ROD CELLS IN WIDTH	CRITICAL NUMBER OF FUEL ROD CELLS IN LENGTH	NUMBER OF Gd PINS
	a		i	j	
28	9.68 ± 0.01	13.3 ± 0.2	25	29.82	30
50	12.42 ± 0.01	13.1 ± 0.3	20	17.51	12
40	15.37 ± 0.01	13.1 ± 0.2	15	15.94	9
36	19.35 ± 0.02	13.1 ± 0.3	15	12.87	6
52	24.87 ± 0.01	13.1 ± 0.3	20	12.54	8

Figure B.4. Plan View of Experiments with no Poison Loaded

TABLE B.IV

PHYSICAL DATA FOR EXPERIMENTS WITH NO POISONS ADDED

EXP NO	CELL LATTICE PITCH (mm)	NUMBER OF DRILLED LATTICE HOLES ALONG LENGTH	NUMBER OF DRILLED LATTICE HOLES ALONG WIDTH	UNDRILLED POLYPROPYLENE TEMPLATE OVERHANG IN LENGTH (mm) (MEASURED FROM CELL EDGE TO TEMPLATE EDGE)	UNDRILLED POLYPROPYLENE TEMPLATE OVERHANG IN WIDTH (mm) (MEASURED FROM CELL EDGE)	DRILLED TEMPLATE HOLE SIZE (mm)	POLYPROPYLENE TEMPLATE WIDTH (mm)
	a	b	c	d	e	f	g
21	9.68 ± 0.01	40	25	60.40	25.05	6.05 ± 0.10	292 ± 1
43	12.42 ± 0.01	30	20	67.70	21.85	6.02 ± 0.05	292 ± 1
13	15.37 ± 0.01	32	15	8.08	30.78	6.02 ± 0.08	292 ± 1
32	19.35 ± 0.02	25	15	12.12	0.92	6.02 ± 0.10	292 ± 1
51	24.87 ± 0.01	20	20	5.30	5.30	5.97 ± 0.08	508 ± 1

EXP NO	CELL LATTICE PITCH (mm)	AVERAGE TEMPLATE THICKNESS (OF ALL 4 TEMPLATES) (mm)	AVERAGE SLOT WIDTH (mm)	AVERAGE SLOT DEPTH (mm)	NUMBER OF FUEL ROD CELLS IN WIDTH	CRITICAL NUMBER OF FUEL ROD CELLS IN LENGTH
	a		h		i	j
21	9.68 ± 0.01	13.3 ± 0.2	---	---	25	22.88
43	12.42 ± 0.01	13.1 ± 0.3	---	---	20	14.70
13	15.37 ± 0.01	13.1 ± 0.2	---	---	15	13.11
32	19.35 ± 0.02	13.1 ± 0.2	---	---	15	11.01
51	24.87 ± 0.01	13.1 ± 0.3	---	---	20	10.40

Figure B.5. Plan View of Experiments with Cadmium Plate in Edge Row

TABLE B.V

PHYSICAL DATA FOR EXPERIMENTS WITH CADMIUM PLATES LOADED IN EDGE ROW

EXP NO	CELL LATTICE PITCH (mm)	NUMBER OF DRILLED LATTICE HOLES ALONG LENGTH	NUMBER OF DRILLED LATTICE HOLES ALONG WIDTH	UNDRILLED POLYPROPYLENE TEMPLATE OVERHANG IN LENGTH (mm) (MEASURED FROM CELL EDGE TO TEMPLATE EDGE)	UNDRILLED POLYPROPYLENE TEMPLATE OVERHANG IN WIDTH (mm) (MEASURED FROM CELL EDGE)	DRILLED TEMPLATE HOLE SIZE (mm)	POLYPROPYLENE TEMPLATE WIDTH (mm)
	a	b	c	d	e	f	g
22	9.68 ± 0.01	40	25	60.40	25.05	6.05 ± 0.10	292 ± 1
45	12.42 ± 0.01	30	20	67.70	21.85	6.02 ± 0.05	292 ± 1
14	15.37 ± 0.01	32	15	8.08	30.78	6.02 ± 0.08	292 ± 1
34	19.35 ± 0.02	25	15	12.12	0.92	6.02 ± 0.10	292 ± 1
54	24.87 ± 0.01	20	20	5.30	5.30	5.97 ± 0.08	508 ± 1

EXP NO	CELL LATTICE PITCH (mm)	AVERAGE TEMPLATE THICKNESS (OF ALL 4 TEMPLATES) (mm)	AVERAGE SLOT WIDTH (mm)	AVERAGE SLOT DEPTH (mm)	NUMBER OF FUEL ROD CELLS IN WIDTH	CRITICAL NUMBER OF FUEL ROD CELLS IN LENGTH
	a		h		i	j
22	9.68 ± 0.01	13.3 ± 0.2	4.72 ± 0.05	4.83 ± 0.18	24	27.12
45	12.42 ± 0.01	13.1 ± 0.3	4.57 ± 0.05	4.88 ± 0.20	19	16.49
14	15.37 ± 0.01	13.1 ± 0.2	4.62 ± 0.05	4.80 ± 0.10	14	15.26
34	19.35 ± 0.02	13.1 ± 0.3	4.62 ± 0.08	4.62 ± 0.25	14	12.15
54	24.87 ± 0.01	13.1 ± 0.3	4.55 ± 0.08	4.98 ± 0.18	18	11.10

Figure B.6. Plan View of Experiments with Cadmium Plate in Middle Row

TABLE B.VI

PHYSICAL DATA FOR EXPERIMENTS WITH CADMIUM PLATES LOADED IN MIDDLE ROW

EXP NO	CELL LATTICE PITCH (mm)	NUMBER OF DRILLED LATTICE HOLES ALONG LENGTH	NUMBER OF DRILLED LATTICE HOLES ALONG WIDTH	UNDRILLED POLYPROPYLENE TEMPLATE OVERHANG IN LENGTH (mm) (MEASURED FROM CELL EDGE TO TEMPLATE EDGE)	UNDRILLED POLYPROPYLENE TEMPLATE OVERHANG IN WIDTH (mm) (MEASURED FROM CELL EDGE)	DRILLED TEMPLATE HOLE SIZE (mm)	POLYPROPYLENE TEMPLATE WIDTH (mm)
	a	b	c	d	e	f	g
24	9.68 ± 0.01	40	25	60.40	25.05	6.05 ± 0.10	292 ± 1
48	12.42 ± 0.01	30	20	67.70	21.85	6.02 ± 0.05	292 ± 1
16	15.37 ± 0.01	32	15	8.08	30.78	6.02 ± 0.08	292 ± 1
39	19.35 ± 0.02	25	15	12.12	0.92	6.02 ± 0.10	292 ± 1
57	24.87 ± 0.01	20	20	5.30	5.30	5.97 ± 0.08	508 ± 1

EXP NO	CELL LATTICE PITCH (mm)	AVERAGE TEMPLATE THICKNESS (OF ALL 4 TEMPLATES) (mm)	AVERAGE SLOT WIDTH (mm)	AVERAGE SLOT DEPTH (mm)	NUMBER OF FUEL ROD CELLS IN WIDTH	CRITICAL NUMBER OF FUEL ROD CELLS IN LENGTH
	a		h		i	j
24	9.68 ± 0.01	13.3 ± 0.2	4.72 ± 0.05	4.83 ± 0.18	24	29.80
48	12.42 ± 0.01	13.1 ± 0.3	4.57 ± 0.05	4.88 ± 0.20	18	21.87
16	15.37 ± 0.01	13.1 ± 0.2	4.62 ± 0.05	4.80 ± 0.10	14	21.94
39	19.35 ± 0.02	13.1 ± 0.3	4.62 ± 0.08	4.62 ± 0.25	14	19.07
57	24.87 ± 0.01	13.1 ± 0.3	4.55 ± 0.08	4.98 ± 0.18	18	17.31

Figure B.7. Plan View of Experiments with Boral Plate in Edge Row

TABLE B.VII

PHYSICAL DATA FOR EXPERIMENTS WITH BORAL PLATES LOADED IN EDGE ROW

EXP NO	CELL LATTICE PITCH (mm)	NUMBER OF DRILLED LATTICE HOLES ALONG LENGTH	NUMBER OF DRILLED LATTICE HOLES ALONG WIDTH	UNDRILLED POLYPROPYLENE TEMPLATE OVERHANG IN LENGTH (mm) (MEASURED FROM CELL EDGE TO TEMPLATE EDGE)	UNDRILLED POLYPROPYLENE TEMPLATE OVERHANG IN WIDTH (mm) (MEASURED FROM CELL EDGE)	DRILLED TEMPLATE HOLE SIZE (mm)	POLYPROPYLENE TEMPLATE WIDTH (mm)
	a	b	c	d	e	f	g
23	9.68 ± 0.01	40	25	60.40	25.05	6.05 ± 0.10	292 ± 1
46	12.42 ± 0.01	30	20	67.70	21.85	6.02 ± 0.05	292 ± 1
15	15.37 ± 0.01	32	15	8.08	30.78	6.02 ± 0.08	292 ± 1
35	19.35 ± 0.02	25	15	12.12	0.92	6.02 ± 0.10	292 ± 1
55	24.87 ± 0.01	20	20	5.30	5.30	5.97 ± 0.08	508 ± 1

EXP NO	CELL LATTICE PITCH (mm)	AVERAGE TEMPLATE THICKNESS (OF ALL 4 TEMPLATES) (mm)	AVERAGE SLOT WIDTH (mm)	AVERAGE SLOT DEPTH (mm)	NUMBER OF FUEL ROD CELLS IN WIDTH	CRITICAL NUMBER OF FUEL ROD CELLS IN LENGTH
	a		h		i	j
23	9.68 ± 0.01	13.3 ± 0.2	4.72 ± 0.05	4.83 ± 0.18	24	27.77
46	12.42 ± 0.01	13.1 ± 0.3	4.57 ± 0.05	4.88 ± 0.20	19	16.91
15	15.37 ± 0.01	13.1 ± 0.2	4.62 ± 0.05	4.80 ± 0.19	14	15.77
35	19.35 ± 0.02	13.1 ± 0.3	4.62 ± 0.08	4.62 ± 0.25	14	12.30
55	24.87 ± 0.01	13.1 ± 0.3	4.55 ± 0.08	4.98 ± 0.18	18	11.17

Figure B.8. Plan View of Experiments with Boral Plate in Middle Row

TABLE B.VIII

PHYSICAL DATA FOR EXPERIMENTS WITH BORAL PLATES LOADED IN MIDDLE ROW

EXP NO	CELL LATTICE PITCH (mm)	NUMBER OF DRILLED LATTICE HOLES ALONG LENGTH	NUMBER OF DRILLED LATTICE HOLES ALONG WIDTH	UNDRILLED POLYPROPYLENE TEMPLATE OVERHANG IN LENGTH (mm) (MEASURED FROM CELL EDGE TO TEMPLATE EDGE)	UNDRILLED POLYPROPYLENE TEMPLATE OVERHANG IN WIDTH (mm) (MEASURED FROM CELL EDGE)	DRILLED TEMPLATE HOLE SIZE (mm)	POLYPROPYLENE TEMPLATE WIDTH (mm)
	a	b	c	d	e	f	g
25	9.68 ± 0.01	40	25	60.40	25.05	6.05 ± 0.10	292 ± 1
49	12.42 ± 0.01	30	20	67.70	21.85	6.02 ± 0.05	292 ± 1
20	15.37 ± 0.01	32	15	8.08	30.78	6.02 ± 0.08	292 ± 1
38	19.35 ± 0.02	25	15	12.12	0.92	6.02 ± 0.10	292 ± 1
58	24.87 ± 0.01	20	20	5.30	5.30	5.97 ± 0.08	508 ± 1

EXP NO	CELL LATTICE PITCH (mm)	AVERAGE TEMPLATE THICKNESS (OF ALL 4 TEMPLATES) (mm)	AVERAGE SLOT WIDTH (mm)	AVERAGE SLOT DEPTH (mm)	NUMBER OF FUEL ROD CELLS IN WIDTH	CRITICAL NUMBER OF FUEL ROD CELLS IN LENGTH
	a		h		i	j
25	9.68 ± 0.01	13.3 ± 0.2	4.72 ± 0.05	4.83 ± 0.18	24	37.32
49	12.42 ± 0.01	13.1 ± 0.3	4.57 ± 0.05	4.88 ± 0.20	18	27.01
20	15.37 ± 0.01	13.1 ± 0.2	4.62 ± 0.05	4.80 ± 0.10	14	28.29
38	19.35 ± 0.02	13.1 ± 0.3	4.62 ± 0.08	4.62 ± 0.25	14	23.00
58	24.87 ± 0.01	13.1 ± 0.3	4.55 ± 0.08	4.98 ± 0.18	18	18.89

Figure B.9. Elevation View of Experiment Assembly

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