CRITICAL EXPERIMENTS SUPPORTING
CLOSE PROXIMITY WATER STORAGE
OF POWER REACTOR FUEL

SUMMARY REPORT

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PREPARED FOR THE
DEPARTMENT OF ENERGY
FUEL CYCLE PROGRAM OFFICE
UNDER CONTRACT EY-77-C-09-1001
FORM 189 NUMBER 210.2

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Critical Experiments Supporting Close Proximity
Water Storage of Power Reactor Fuel
Technical Progress Report

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ABSTRACT

Close-packed storage of LWR fuel assemblies is needed in order to expand the capacity of existing underwater storage pools. This increased capacity is required to accommodate the large volume of spent fuel produced by prolonged onsite storage. To provide benchmark criticality data in support of this effort, 20 critical assemblies were constructed that simulated a variety of close-packed LWR fuel storage configurations. Criticality calculations using the Monte Carlo KENO-IV code were performed to provide an analytical basis for comparison with the experimental data. Each critical configuration is documented in sufficient detail to permit the use of these data in validating calculational methods according to ANSI Standard N16.9-1975.

Lynchburg Research Center Report BAW-1484-7
July 1979
Critical Experiment, Power Reactor Fuel
Storage, Benchmark Experiments

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1. INTRODUCTION

Spent nuclear fuel is stored underwater to provide biological shielding and to remove decay heat. Fuel storage pools exist for this purpose at all U.S. nuclear power stations. Plant operators originally anticipated that onsite fuel storage would be an interim arrangement pending offsite shipment to fuel reprocessing or long-term storage facilities. Accordingly, the onsite fuel storage pools were designed to accommodate only a limited quantity of fuel. This moderate capacity was sufficient for expected operating and storage needs. However, long delays were encountered in closing the nuclear fuel cycle and in making provisions for long-term storage of high level commercial nuclear wastes. As a result, nuclear power station operators have been required to store their spent fuel much longer than was originally anticipated, and there has been a concomitant need to optimize use of available onsite storage capacity. This optimum use requires that fuel assemblies be stored with the minimum spacing consistent with nuclear criticality safety.

To compensate for the increased reactivity that arises from storing fuel assemblies closer together, neutron absorbing materials in the form of pins or plates are required between the assemblies in a storage array. Experimental data are necessary to validate the methods used to calculate the k_{eff} of such a configuration. Since prior critical experiments have mocked up only reactor core or shipping container conditions, no directly applicable experimental data have been available. At an August 1975 meeting held in Rocky Flats, Colorado, to discuss needed benchmark experiments, high priority was assigned to critical experiments simulating spent fuel storage.¹

In July 1977, The Babcock & Wilcox Company (B&W) was awarded a contract by the U.S. Energy Research and Development Administration (now the U.S. Department of Energy) to conduct a series of critical experiments that simulate close-packed storage of LWR-type fuel. These experiments, which provide a body of benchmark data suitable for validating calculational methods used to predict the k_{eff} of nuclear fuel storage in a close-packed, heavily poisoned array,

are described herein. Each benchmark core was analyzed using the KENO IV computer code to determine its calculated k_{eff} .

This report summarizes all the experimental and calculational results obtained under the contract. In some instances, data previously reported in technical progress reports²⁻⁷ have been re-analyzed, and the results given herein may differ slightly from those reported earlier.

2. SUMMARY

Low-enriched UO_2 fuel pins in a water-moderated lattice were used to construct 20 critical assemblies that simulated a variety of close-packed LWR fuel storage configurations. The critical assemblies consisted of nine LWR-type fuel assemblies (clusters) grouped in a 3×3 array. Both the spacing and the material between the fuel clusters were varied to provide numerous critical configurations. All pertinent data for each critical assembly are documented in enough detail to permit use of these data for validating calculational methods according to ANSI Standard N16.9-1975.

To provide an analytical basis for comparison with the experimental data, criticality calculations using the Monte Carlo KENO IV code were performed. The measured and calculated values for k_{eff} are summarized below. These data show that the calculational model underestimates k_{eff} when separation between arrays is greater than one pin pitch and that the degree of underestimation increases with wider spacing.

Measured Vs Calculated k_{eff} Values

Spacing between arrays, inches	Core	Calculated by KENO	Measured	Calculated minus measured
None	I	0.998 ± 0.006	1.0002 ± 0.0005	-0.002
	II	1.007 ± 0.004	1.0001 ± 0.0005	+0.007
0.644	III	0.999 ± 0.004	1.0000 ± 0.0006	-0.001
	IV	1.004 ± 0.007	0.9999 ± 0.0006	+0.004
	XI	1.015 ± 0.004	1.0000 ± 0.0006	+0.015
	XII	1.008 ± 0.005	1.0000 ± 0.0010	+0.008
	XIV	1.003 ± 0.004	1.0001 ± 0.0010	+0.003
	XV	0.995 ± 0.005	0.9998 ± 0.0016	-0.005
	XVII	0.993 ± 0.005	1.0000 ± 0.0010	-0.007
	XIX	0.991 ± 0.004	1.0002 ± 0.0010	-0.009
1.288	V	1.005 ± 0.005	1.0000 ± 0.0007	+0.005
	VI	0.998 ± 0.004	1.0097 ± 0.0012	-0.012
	XII	0.991 ± 0.005	1.0000 ± 0.0007	-0.009
	XVI	0.990 ± 0.005	1.0001 ± 0.0019	-0.010
	XVIII	1.005 ± 0.005	1.0002 ± 0.0011	+0.005
	XX	0.997 ± 0.005	1.0003 ± 0.0011	-0.003
1.932	VII	0.994 ± 0.005	0.9998 ± 0.0009	-0.006
	VIII	1.003 ± 0.005	1.0083 ± 0.0012	-0.005
	X	0.988 ± 0.004	1.0001 ± 0.0009	-0.012
	XXI	0.981 ± 0.004	0.9997 ± 0.0015	-0.019
2.576	IX	0.987 ± 0.005	1.0030 ± 0.0009	-0.016

3. DESCRIPTION OF FACILITY

3.1. Facility

The experiments were performed at B&W's Lynchburg Research Center in the company's CX-10 critical facility. CX-10 is a tank-type facility licensed for the performance of critical experiments with water-moderated UO_2 and mixed oxide fuel lattices. Although the facility is licensed to use either light or heavy water as a moderator, only light water was used in this series of experiments. The critical assemblies were constructed inside a 152.4 cm (5 ft)-diameter by 198 cm (6.5 ft)-high core tank with 1.27 cm (0.5 in.)-thick aluminum walls (see Figure 1).

The core tank is located inside a steel tank 274 cm (9 ft) in diameter and is supported on a skirt that holds it about 75 cm above the base of the larger tank. The larger steel tank can also serve as a core tank to accommodate larger critical assemblies. The top and bottom egg-crate grid plates consist of 2.54 cm (1 in.)-wide slotted aluminum strips interlocked to form a square matrix. The strips are 0.406 cm (0.160 in.)-thick and are spaced on 1.636 ± 0.005 cm (0.644 ± 0.002 in.) centers. A 5.08-cm (2 in.)-thick aluminum base plate 2.54 cm (1 in.) above the bottom of the core tank supports the fuel rods. Unless otherwise specified, moderator heights are referenced from the top of this base plate.

Figure 2 shows the moderator fill system used. The maximum pump capacity is about 2.2 liters per second (35 gpm). The moderator system components are either aluminum or stainless steel except for the 17,000-liter (4500 gal.) dump tank. The dump tank is constructed of amercoated carbon steel.

The safety blades are 0.2 cm (0.08 in.) thick boral about 20 cm (7.9 in.) wide by 180 cm (70.9 in.) long. All blades are thin enough to pass between the rows of fuel rods, and webs are cut away in the top grid where blade entry is necessary. During this series of experiments, the blades performed a safety function only and were fully withdrawn during operation.

The nuclear instrumentation and control system is basically the same as that used in earlier light water experiments.⁸ The neutron detectors are conventional pulse counters and ionization chambers located at the outside wall of the core tank in standpipes.

The moderator level in the core tank is sensed by a remotely operated conductivity probe. The probe is moved by a Selsyn motor driven by a manually operated Selsyn transmitter at the control console. The moderator level indicated at the console by a Veeder Root counter is calibrated to an accuracy of ± 0.2 cm. Incremental changes in moderator level can be measured to an accuracy of ± 0.02 cm.

3.2. Fuel Rods

The fuel rods are aluminum tubes filled with sintered pellets of 2.46% enriched UO_2 . Aluminum plugs 0.318 cm thick are welded to the ends to seal the tubes. A 2.5-cm void space between the top pellet and the end plug is filled with Kaowool. Figure 3 shows the average dimensions of a fuel rod.

Table 1 is a summary of the physical properties of the fuel rods based on measurements of randomly selected samples. The standard deviation $\sigma(x)$ and standard deviation of the mean $\sigma(\bar{x})$ were computed from these equations:

$$\sigma^2(x) = \frac{\sum (x - \bar{x})^2}{N - 1},$$

$$\sigma^2(\bar{x}) = \frac{\sum (x - \bar{x})}{N(N - 1)}.$$

The impurities are given as the summation of $N_i \sigma_i$ where N_i is the concentration of each impurity per cm^3 of the oxide fuel, and σ_i is the corresponding microscopic absorption cross section at 2200 m/s.

The physical and chemical properties of the fuel rods reported herein are taken from reports of an earlier experimental program at B&W when these rods were first used.^{9,10} Additional details are given in the referenced reports.

3.3. B_4C Pins

The B_4C pins are aluminum tubes filled with natural B_4C powder ranging from 30 to 50 mesh. The aluminum tubes are 1.113 cm in outside diameter and have a wall thickness of 0.089 cm. The bottom ends are sealed with welded aluminum

plugs 0.952 cm long, and the tops are sealed with removable cork plugs. The pins contain 156 g of B_4C , which constitutes a column long enough to span the full core height. The B_4C within the tubes extends about 30 cm above the moderator level (Figure 6). The B_4C is compacted to 0.879 ± 0.001 g/cm. A certified chemical analysis of the B_4C powder is given in Table 2.

3.4. Unit Assemblies

The unit assemblies are 14 by 14 rod assemblies that can be moved as units; each has its own top, center, and bottom grid plates. Fuel rods occupy 192 of the rod positions, and threaded aluminum rods occupy the corner positions. The lower ends of the threaded rods have fittings which fit into a large bottom grid for alignment. A photograph of a partially loaded unit assembly is shown in Figure 4.

Each grid plate is a 9.016-inch-square 6061 aluminum plate. The bottom, center, and top grids are 1.000, 0.125, and 0.500 inch thick, respectively. Figure 8 illustrates the vertical position of the unit assembly grids. All rods are spaced on a square pitch of 0.644 inch. The type 6061 aluminum corner rods of each unit assembly are 0.500 inch in diameter.

3.5. Stainless Steel Sheets

Four identical type 304 stainless steel sheets were fabricated to isolate the nine unit assemblies from one another. Each sheet is 91.6 cm wide by 156 cm high and is 0.462 ± 0.008 cm thick. Two slots, 0.551 ± 0.038 cm wide and extending 78 cm up each sheet, are centered 12.18 ± 0.02 cm on each side of the vertical centerline, so that the four sheets may be assembled in egg-crate fashion. The analytical composition of the type 304 stainless steel is given in Table 3.

3.6. Borated Aluminum Sheets

Twenty-four lightly borated aluminum sheets were custom-made for these critical experiments by Kawecki Berylco Industries, Inc. (KBI). The alloy is similar to KBI's 4 wt % boron nuclear grade product, except that the boron content was reduced for our application. Six sets of the boron aluminum alloy sheets were fabricated. Two sets had the same nominal boron loading of about 1.62 wt %. Loading in the remaining four sets varied from about 0.10 to about 1.25 wt % boron.

Each sheet is 91.6 cm wide by 156 cm high and is 0.645 ± 0.005 cm thick. Two slots, 0.711 ± 0.013 cm wide and extending 78 cm up each sheet, are centered 12.18 cm on each side of the vertical centerline so that the four sheets may be assembled in egg-crate fashion. The elemental composition of each set is given in Table 4.

3.7. Core Assemblies

The nine fuel clusters were supported within the core tank by two different methods:

In the first, large top and bottom grids held fuel rods and B_4C pins in place. With this arrangement, benchmark cores consisting of nine square clusters of fuel rods separated by water only and by water and B_4C pins were studied. A core with this type of support is shown in Figure 5, and vertical dimensions are given in Figure 6.

In the second method, the large top grid was removed and unit assemblies were positioned on the large bottom grid. The fuel assemblies were vertically aligned by specially designed locating bars and fastening plates. This specially designed hardware permitted the fuel assemblies to be moved and aligned at varying spacings without the large top grid. This feature was necessary to accommodate the loading of the isolation sheets inside the core tank. With this arrangement, benchmark cores consisting of nine unit assemblies separated by water only, by water and stainless steel sheets, and by water and borated aluminum sheets were studied. A core with this type of support is shown in Figure 7, and vertical dimensions are given in Figure 8. Figure 9 shows how the unit assemblies were grouped among the isolation sheets.

4. BORON LOADING OF BORATED ALUMINUM SHEETS

Neutron transmission analysis was used to evaluate the uniformity of boron distribution in each of the borated isolation sheets and to measure the set-to-set variation of average boron concentration. Basically, this analysis consisted of measuring the attenuation of a thermal neutron beam passed through 15 different points on each sheet.

Figure 10 illustrates how these measurements were made. The source of neutrons was the Lynchburg Pool Reactor (LPR), a 1-MW swimming pool research reactor. As shown in Figure 10, a 4-inch-ID dry aluminum thimble was used to extract and collimate a beam of neutrons from near the LPR core. A 2-inch-diameter BF_3 detector was positioned coaxially above the thimble to measure the attenuation of the neutron beam as it passed through the borated sheet placed on the work surface. Measurements were taken at 15 points on each sheet, distributed as shown in Figure 11.

The quantity measured was ϕ/ϕ_0 . ϕ_0 is the count rate attributable to neutrons below the cadmium cut-off energy (~ 0.4 eV) with a 0.25-inch-thick sheet of aluminum (unborated) in the beam. ϕ is the count rate attributable to neutrons below the cadmium cut-off energy with the borated isolation sheet in the beam. The quantity $-\ln(\phi/\phi_0)$ is directly proportional to the boron content at that point on the sheet.

The vendor's chemical boron analysis and the average relative value obtained from neutron transmission for each set of sheets are tabulated in Table 5. The vendor values are a measure of absolute boron concentration. The relative values obtained from neutron transmission analysis, however, are a more precise measure of the change in average boron concentration from one set of sheets to another. Accordingly, the vendor analyses were used to determine a calibration constant that, when multiplied by the relative value, gives the best measure of boron content. The absolute measurements (vendor analyses) with the smallest uncertainty were given the greatest weight in determining the calibration constant. This process is outlined in Table 5.

The best value for the average boron concentration in each set is listed in the last column of Table 5. The uncertainties listed represent one standard deviation. The measured deviation of each point on a sheet from the average of the set is tabulated in Appendix A.

5. CRITICAL ASSEMBLY MEASUREMENTS

Twenty-one benchmark cores were loaded and brought critical. These cores are diagrammed in Figures 12 through 24. The data taken for each core are summarized in Tables 6 and 7.

Core I is a reference cylindrical core containing 438 fuel rods. All of the remaining cores consist of nine fuel pin clusters grouped in a 3 by 3 array and spaced from 0 to 4 pin pitches apart. Use of the following materials within the space separating the fuel bundles provided various critical loadings:

1. Water only.
2. Water and B_4C -filled pins.
3. Water and stainless steel sheets.
4. Water and borated aluminum sheets.

Two pairs of core loadings (V/VI and VII/VIII) were identical except for B_4C pin location.

Excess reactivity was controlled by dissolving boric acid (H_3BO_3) in the moderator (demineralized water). The boron concentrations (ppm) given in this report are defined as grams of natural boron per million cm^3 of moderator at 25C. The boron concentration for each core was measured by titration against a standard KOH solution. These measurements have a standard deviation of ± 3 ppm at all concentrations.

Reactivity versus water height data were taken as a measure of moderator boron worth and to permit the experimental values of k_{eff} to be normalized to a uniform water level. $\Delta\rho/\Delta H$ measurements were taken in the following manner:

1. The moderator level was slowly increased until the reactor was slightly supercritical.
2. The stable reactor period was measured by timing the rise in neutron flux level through several decades.
3. The moderator level was dropped until the reactor was just critical. The decrement in water level between the supercritical and just-critical conditions is the ΔH reported in Tables 6 and 7. As discussed in section 3,

this decrement is measurable to ± 0.02 cm by a remotely operated conductivity probe.

4. The reactor period was converted to reactivity units (ρ/β) using the in-hour equation. This is the $\Delta\rho$ reported in Tables 6 and 7.

Analysis of the experimental data is described in section 6.

6. ANALYSIS OF EXPERIMENTAL DATA

6.1. General

All core loadings are summarized in Tables 6 and 7. To provide a more usable body of benchmark data for validating calculational methods, further analysis of the data was performed. The analysis, discussed in this section, deals with two aspects of data reduction:

1. Computing the Δk that would result from adjusting the moderator height of each benchmark core from its actual level to some uniform level — this uniform level was 145.00 cm for cores using the continuous upper grid and 150.00 cm for the cores using the unit assemblies.
2. Estimating the magnitude of uncertainty in the experimental k_{eff} that arises from uncertainties in experimental parameters.

The results of the final data analysis for all cores are summarized in Tables 8 and 9.

6.2. Reactivity Worth of Moderator Height

Increments (or decrements) in moderator level and the reactivity changes that they precipitate are readily measurable. Accordingly, the $\Delta\rho/\Delta H$ data were taken to provide a basis for correlating certain experimental parameters with core reactivity. This correlation was used to compute the Δk that results from adjusting all moderator heights to a uniform level and to estimate the uncertainty in the experimental k_{eff} that arises from uncertainties in experimental parameters.

To put the $\Delta\rho/\Delta H$ data in useful form, those points that correspond to an average moderator height of less than 135 cm were fitted to a linearized form of

$$\frac{\delta\rho}{\delta H} = \frac{C}{(H_f + \lambda)^3} \quad (1)$$

where H_f is the moderator height above the bottom of the fuel and C and λ are fitting constants. The fit is shown in Figure 25, where C and λ have been determined to have values of $8.225 \times 10^6 \text{ } \phi/\text{cm}^2$ and 9.26 cm, respectively. Above a moderator level of 135 cm, the curve is allowed to deviate from the analytical least-squares fit to track the experimental values.

From equation 1 and Figure 25, $d\rho/dh$ as a function of H was determined. By integrating this function between H and H' , the reactivity worth of a change in moderator height from H to H' was calculated. The results of this integration are shown in Figures 26 and 27.

Figure 26 applies to cores I through IX and shows the difference in reactivity between a core with a moderator height of 145.00 cm and the same core at other moderator heights. The adjustments for cores I-IX are listed in Table 8.

Figure 27 applies to cores X through XXI and is a plot of the difference in reactivity between a core with a moderator height of 150.00 cm and the same core at other moderator heights. The adjustments for cores X through XXI are listed in Table 9.

Figures 26 and 27 have an estimated uncertainty of $\pm 4\%$. Of this, 3% is attributed to the experimental measurement of $\delta\rho/\delta H$. The additional 1% is for error in the least-squares fit. The delayed neutron fraction was assigned a value of 0.0075 ± 0.0005 .

6.3. Reactivity Worth of Moderator Boron

Equation 1 was also used to estimate the moderator boron worth for cores with one pin pitch separation between the fuel clusters. Knowledge of the boron worth is useful since uncertainties in moderator boron concentration can then be expressed in terms of uncertainties in experimental k_{eff} .

The first step in determining boron worth is to integrate equation 1. Thus, the reactivity difference (due to moderator height) between runs 2268 and 2271 of core III is

$$\rho = \frac{C/2}{(H + \lambda)^2} \bigg/ \frac{H_2}{H_1} = 135.4 \pm 5.4\phi. \quad (2)$$

Since the only other difference between these two runs is 51 ± 4 ppm of moderator boron, we conclude (to a first-order approximation) that $\delta\rho/dB$ is 2.7 ± 0.2

¢/ppm for core III. Likewise, the reactivity difference due to moderator height between runs 2360 and 2364 of core XI was 164.6 ± 6.6 ¢. Since the only other difference between these runs is 69 ± 4 ppm of moderator boron, we conclude that $\delta\rho/\delta B$ is 2.4 ± 0.2 ¢/ppm for core XI.

To convert uncertainty in units of moderator boron to units of $\Delta k/k$ the value of 2.55 ¢/ppm (which is the average of measurements reported herein for cores III and XI) was used for all cores with 1 pin pitch separation. For cores with 0, 2, 3, and 4 pin pitch separations, we did not attempt to measure moderator boron worth accurately. However, small moderator boron changes which were made to make final adjustments to a benchmark core's critical moderator height show worths of about 2 ± 1 , 3 ± 1 , 4 ± 1 , and 4 ± 1 ¢/ppm respectively. Accordingly, these worths were used to convert moderator boron uncertainty to units of $\Delta k/k$ for cores with 0, 2, 3, and 4-pin pitch separation.

6.4. Borated Isolation Sheets

An area of concern during the experiments has been whether or not the boron loading of the isolation sheets was uniform enough to give good experimental results. Figure 27 is a plot of moderator boron concentration versus the boron content of the isolation sheets for benchmark loadings of 1 and 2 pin pitch separation. The uniformity of the data, as well as the almost identical results from two different sets of isolation sheets with the same nominal loading, demonstrates that the boron uniformity is adequate.

From Figure 27 and the standard deviation on the average boron loading of each set, we estimate that for cores XV and XVI (which use the set of isolation sheets with the largest standard deviation), the uncertainty in the boron loading produces an uncertainty in the just-critical condition that is equivalent to 8 ppm of moderator boron. For all the other cores containing isolation sheets, the uncertainty in the core boron loading produced an uncertainty equivalent to 4 ppm or less of moderator boron. The uncertainty in Δk attributable to this factor is listed in Table 9 for cores XIII through XXI.

7. COMPUTATIONAL ANALYSIS

7.1. Introduction

The neutron multiplication factor (k_{eff}) of each benchmark core was calculated using the Monte Carlo criticality code KENO IV.¹¹ The 123-group XSDRN cross section set was used.¹² Resonance self-shielding was accounted for in the uranium-238 isotope only. Self-shielding corrections were made with the NITAWL code from the AMPX package.¹³ This section describes the calculational model and its development. The KENO input and output for all 21 benchmark loadings are listed in the Appendixes.

The diffusion code PDQ-7 was used to compute the k_{eff} of selected benchmark cores. The calculational method for PDQ-7 is also described in this section.

7.2. KENO IV Calculations

7.2.1. Cross Section Preparation

The 123-group XSDRN cross section set was used. The XSDRN library was generated by combining the GAMII library for epithermal groups and the THERMOS library for thermal groups. The XSDRN library was obtained from ORNL in binary coded decimal (BCD) format, as well as an auxiliary program — AIM — that was used to convert the library from BCD to binary format.

The NITAWL code was used to calculate the resonance self-shielding for uranium-238 and to develop the working library for the KENO calculation. Some of the important resonance data for NITAWL input are as follows:

1. Dancoff correction factor, C .
2. Effective moderator cross section per ^{238}U atom (60.73 b).
3. First moderator scattering cross section per ^{238}U atom (7.74 b).

Several methods are used to calculate the Dancoff correction factor. Ours was to add the values tabulated in Table 2-25 of ANL-5800¹⁴ for the pin geometry in question:

$$C = \sum C_i.$$

To account for partial transparency of the fuel pins to neutrons, the Dancoff correction factor was modified as follows¹⁵:

$$C_{\text{eff}} = \frac{1.1C}{1 + 0.1C}.$$

The Dancoff correction values used in NITAWL for the interior, edge, and corner fuel pins of each assembly were 0.1925, 0.1346, and 0.0868, respectively.

7.2.2. KENO Modeling Assumptions

The portions of the core that were mocked up by the basic KENO computer model are shown in Figure 29. The computer representation explicitly modeled each fuel rod, each B_4C pin, the isolation sheets, the moderator, and the core tank in the X-Y direction. The fuel and support structure above the water were not represented in the basic computer model. The extent to which this assumption influenced the calculated results is discussed in reference 4. It was found that when the moderator level is much less than 145.0 cm, ignoring the dry fuel in the core model introduces a very slight negative bias in the calculated k_{eff} . However, all benchmark cores were analyzed at a uniform moderator height of 145.0 or 150.0 cm; at these water heights, it was found that the fuel and structure above the moderator did not contribute discernibly to neutron multiplication.

7.2.3. KENO IV Benchmark Core Models

There were three distinct sets of core geometries:

1. Core I — cylindrical critical array of 438 fuel pins, constructed as a base case (Figure 12).
2. Cores II through IX — Nine square fuel pin clusters, each 14 pins on a side, arranged in a 3 by 3 array. The fuel clusters were spaced varying distances apart and were vertically aligned by continuous upper and lower grids. In some cases B_4C pins were inserted in the space between the fuel clusters (Figures 13 through 20).
3. Cores X through XXI — Nine square fuel pin bundles, each 14 pins on a side except that the four corner positions of each fuel assembly were occupied by threaded aluminum rods that positioned the three grid plates

and provided the unit assembly framework. The free-standing feature of the unit assemblies was necessary to accommodate the metal isolation sheets used in cores X through XXI. Like cores II through IX, the fuel assemblies were grouped in a 3 by 3 array and spaced varying distances apart (Figures 21 through 24).

7.2.3.1. Cores I Through IX

Since cores I through IX all used the continuous upper and lower grids for fuel pin alignment and spacing, the axial zones used to model the vertical dimension were the same for all nine loadings. The vertical dimensions for cores I through IX are shown in Figure 6.

The KENO model represented each fuel pin in a distinct lattice cell. Each fuel cell consisted of three axial zones. The bottom zone represented the aluminum end plug of the fuel pin resting on the base plate. The center axial zone represented the portion of the fuel pin supported by the bottom grid (1 inch thick). The top axial zone represented the moderated fuel region. As already mentioned, all material above the moderator surface was ignored in the KENO model.

A set of box types with the same axial zones was constructed for the moderator lattice cells and the poison pins. These boxes were used as necessary to fill the volume surrounded by the core boundary. All of these cores were analyzed with a uniform moderator height of 145.0 cm above the base plate.

Type 6061 aluminum alloy was used for the pin cladding, bottom grid, base plate, and core tank. The atom densities used for all materials in cores I through IX are listed in Table 10.

7.2.3.2. Cores X Through XXI

The vertical dimensions for these loadings are shown in Figure 8. Figure 9, an isometric sketch, illustrates the placement of the unit assemblies among the isolation sheets. Figure 4 shows a partially loaded fuel assembly. Frequent reference to these figures will help the reader to understand the modeling details described in this section.

In order to make way for the metal isolation sheets, the continuous upper grid was not used. To support the fuel pins without a continuous upper grid, free-standing unit assemblies were built. Each unit assembly had its own top, bottom,

and center grid plates to maintain the lattice spacing. The unit assemblies were vertically aligned with tie plates and top locating bars fastened to the fuel bundles. Since this positioning hardware was always above the moderator surface, it was not included in the computer model.

The continuous lower grid was kept in the core tank for the second set of critical loadings. It served two purposes:

1. The bottom locating bars that held the metal isolation sheets in position had 1-inch aluminum pins that fit into the lower grid to position the bottom bar.
2. The aluminum rods in the corner of each fuel assembly penetrated 1 inch through the bottom grid plate. These rods fit into the continuous lower grid, thereby positioning the unit assemblies in the core tank.

The bottom grid plate of each fuel assembly was modeled as an aluminum block with 192 holes 0.9525 cm deep and located on 1.6358-cm centers. The block was modeled as 2.54 cm thick and 14 lattice spacings square in the horizontal plane. It rested on the continuous bottom grid and was assumed to be held there by square aluminum pegs extending 1 inch from the four corner positions of each fuel assembly into the continuous lower grid. The continuous lower grid was suspended 0.3175 cm above the base plate.

Each bottom locating bar (there were four) was modeled as an aluminum block 2.54 inches high, one lattice unit wide, and 56 lattice units long. Each block was modeled with a slot 1.5875 cm deep and 0.7112 cm wide centered in the top of the bar and running its entire length. The bars rested on the continuous lower grid against the sides of the bottom grid plate of the center fuel assembly. Since core X used no metal isolation sheets, no bottom locating bars were included in its computer model.

The isolation sheets were modeled from the bottom of the slot in the locating bars to the moderator surface. The isolation sheets were not centered in the slot; rather, they were placed against the edge of the slot nearest the center fuel assembly. Each isolation sheet was assigned a width of 56 lattice units in the computer model. The set screws that fastened the isolation sheets in the locating bars were not modeled.

The core boundary extended from the bottom of the continuous grid to the moderator surface and encompassed an area 56 lattice pitches square. The core

was divided into three axial zones. The bottom zone was the continuous lower grid region, the center zone was the bottom grid plate region, and the top zone was the moderated fuel region, which extended from the top of the bottom grid plates to the moderator surface. One structural member inside the core boundary that was not explicitly modeled was the 0.3175-cm-thick center grid plate, which was located 78.5 cm above the aluminum base plate. The volume fraction of the center grid plate in the moderated fuel assembly region was 0.00205. The center grid plate was homogenized in the moderator inside the space envelope defined by each fuel assembly. Cores X through XXI were analyzed with a uniform moderator height of 150.0 cm above the base plate. Therefore, the active fuel length for all cores (I-XXI) was about the same.

The atomic number densities used for the fuel and aluminum were the same as those used for cores I through IX (Table 10). The other atomic number densities calculated for cores X through XXI are given in Tables 11 and 12.

The model used for the intersection of the two poison plates was that of a cross ($\perp$). Comparison of the cross with simpler models, such as a T-intersection ($\top$) or a bar intersection ($\perp$), showed that there was no difference that the KENO code could discern.

7.2.4. Results of KENO Analysis

The calculations were performed with the KENO IV multigroup Monte Carlo criticality program on B&W's CDC 7600 computer. The original code was modified at B&W to handle large core problems in a CDC computing environment.

Determining the converged value of k_{eff} for a KENO run was not always easy. Each case was run first with 300 neutrons per generation for 60 generations. If convergence was in doubt, the number of neutrons per generation and the number of generations were increased and the case was re-run.

Figures 30 through 50 are plots of k_{eff} versus initial generations skipped for each of the benchmark cores. A list of the calculated values of k_{eff} for each of the 21 benchmark loadings is given in Table 13.

7.3. Diffusion Calculations

Three dimensional PDQ-7¹⁶ calculations were made for cores III, VI, and IX. Core III used boron only in the moderator, core VI used B₄C pins, and core IX was free of boron in any form. The results of the three calculations are presented in Table 14. As expected, the agreement is good for the clean system (core IX) and where the boron is homogenized in the moderator (core III). The agreement is not good for core VI, where the neutron poison (boron) is lumped. We did not attempt special techniques (e.g., the blackness theory) to adjust the cross section of the lumped boron.

The PDQ model used homogenized cross sections generated by NULIF.¹⁷ Sensitivity studies showed that the PDQ model was not sensitive to water reflector thickness of more than 11 cm. Accordingly, the fuel assemblies were surrounded by only 11 cm of water in the PDQ model.

The optimum mesh intervals were found to be 0.818 cm for the water and 3.274 cm for the fuel. All material above the moderator level was ignored. Material below the fuel was mostly aluminum; a homogenized material (0.8244 Al + 0.1756 H₂O) was used to represent the material below the fuel. A copy of the input/output of the PDQ runs is provided in Appendix B.

8. RESULTS AND CONCLUSIONS

A comparison of experimental and calculated results is summarized in Table 15. The results are grouped according to inter-assembly spacing. The data clearly show that the calculational model underpredicts k_{eff} at inter-assembly spacings or more than one lattice pitch (1.636 cm). The degree to which the model underpredicts k_{eff} appears to worsen as the spacing between the fuel assemblies widens. The data are not sufficient to precisely fix the size of the discrepancy in k_{eff} , but it ranges from about -0.5% to -1% $\Delta k/k$ for those cases where the spacing is greater than 1.636 cm.

Table 1. Properties of 2.46% Enriched UO₂ Fuel Rods

<u>Parameter</u>	<u>Average</u>	<u>$\sigma(x)$</u>	<u>$\sigma(\bar{x})$</u>
OD, cm	1.206	0.002	0.0003
Wall thickness, cm	0.081	--	0.003
Wall material	6061-T6 Al	--	--
Pellet diameter, cm	1.030	0.001	0.0005
Total length, cm	156.44	0.41	0.05
Active fuel length, cm	153.34	0.88	0.02
Pellet length, cm	1.914	0.008	0.001
Wt of UO ₂ , g/rod	1305.5	39.7	1.0
Wt U/wt UO ₂ , %	88.13	0.01	0.00
Wt of U, g/rod	1150.5	35.0	0.9
Wt of ²³⁵ U, g/rod	28.29	0.86	0.02
Enrichment, wt 25/wt U, %	2.459	0.002	0.001
Pellet density, g/cm ³	10.29	0.05	0.02
Bulk density, g/cm ³	10.22	0.36	0.01
$\sum N_i \sigma_i$ (summation of impurities, cm ² /cm ³ oxide	$<4 \times 10^{-4}$	--	--

Table 2. Certified Chemical Analysis of B₄C

Total boron	77.8 wt %
Total carbon	20.8 wt %
Anhydrous B ₂ O ₃	0.10 wt %
Boron plus carbon	98.6 wt %
Particle size, 30 to 50 mesh	91.2%

Table 3. Composition of Type 304 Stainless Steel Sheets

<u>Element</u>	<u>Weight %</u>	
	<u>Vendor certification</u>	<u>B&W^(a) analysis</u>
C	0.06	0.05
Mn	1.82	1.67
P	0.027	0.023
S	0.009	0.010
Si	0.55	0.56
Cr	18.16	18.04
Ni	8.59	8.01
Mo	0.16	0.13
Cu	0.08	0.07
Co	0.220	0.198
Fe	Remainder (70.32)	Remainder (71.24)

(a) The B&W values were used in the computer analysis.

Table 4. Composition of Borated Aluminum Sheets

<u>Boron content, wt % B</u>		<u>Starter material, all sets</u>	
<u>Set No.</u>	<u>Avg B content (a)</u>	<u>Al, %</u>	<u>Boron, atom %</u>
1	0.100 ± 2.1%	B: 0.001	19.86 ¹⁰ B
2	0.242 ± 1.4%	Fe: 0.16	80.14 ¹¹ B
3	0.401 ± 4.0%	Si: 0.06	
4	1.257 ± 1.2%	Zn: 0.02	
5	1.614 ± 1.3%	Others: <0.02 each	
5a	1.620 ± 1.4%	Al: Remainder (99.7)	

(a) Density of all sheets = 2.7 g/cm³.

Table 5. B&W Vs Vendor Measurements on Borated Aluminum Sheets

Set No.	Vendor analysis, wt % nat. B	Avg value of B&W-measured $-\ln(\phi/\phi_0)$	Ratio of vendor analyses to mea- sured value of $-\ln(\phi/\phi_0)$	Smoothed vendor analysis, wt % natural B
1	$0.104 \pm 2.9\%$	$0.0548 \pm 1.9\%$	$1.899 \pm 3.5\%$	$0.100 \pm 2.1\%$
2	$0.252 \pm 4.8\%$	$0.132 \pm 1.1\%$	$1.909 \pm 4.9\%$	$0.242 \pm 1.4\%$
3	$0.437 \pm 11\%$	$0.219 \pm 3.9\%$	$1.995 \pm 12\%$	$0.401 \pm 4.0\%$
4	$1.265 \pm 0.9\%$	$0.687 \pm 0.8\%$	$1.841 \pm 1.2\%$	$1.257 \pm 1.2\%$
5	$1.582 \pm 1.8\%$	$0.882 \pm 0.9\%$	$1.794 \pm 2.0\%$	$1.614 \pm 1.3\%$
5a	$1.537 \pm 3.6\%$	$0.885 \pm 0.9\%$	<u>$1.737 \pm 3.7\%$</u>	$1.620 \pm 1.4\%$
		Weighted Avg	$1.830 \pm 0.9\%$	

Table 6. Core Loadings Established With Full Top Grid

Core	Run	Ldg diag. Fig. No.	Spacing between arrays, pin pitches	No. of B ₄ C pins	Moderator temp, C	Moderator boron conc, ppm (±3)	Critical moderator ht, cm (±0.2)	Super- critical moderator ht, cm (±0.2)	Doubling time, s	Δρ, c	ΔH, cm (±0.02)	$\frac{\Delta\rho}{\Delta H}$	$\bar{H}$, cm	$\left(\frac{\Delta\rho}{\Delta H}\right)^{-1/3}$
I	2245	12	--	--	21	0	143.88	147.12	98.5	6.95	3.24	2.15	145.5	0.775
II	2255	13	0	0	18.5	1037	144.29	--	--	--	--	--	--	--
III	2265	14	1	0	18	769	148.63	150.67	202	3.72	2.04	1.82	149.7	0.819
III	2266	14	1	0	18	764	144.88	149.88	64.5	9.70	5.00	1.94	147.4	0.802
III	2267	14	1	0	18	762	140.38	144.80	62.5	10.0	4.42	2.26	142.6	0.762
III	2268	14	1	0	18.5	753	131.32	133.80	95.0	7.20	2.48	2.90	132.6	0.701
III	2269	14	1	0	18	739	120.64	124.26	43.5	13.1	3.62	3.62	122.5	0.651
III	2270	14	1	0	18	721	110.04	111.84	78.0	8.40	1.80	4.67	110.9	0.598
III	2271	14	1	0	18.5	702	100.32	102.09	55.5	11.0	1.77	6.21	101.2	0.544
IV	2282	15	1	84	17	0	145.68	148.94	110	6.33	3.26	1.94	147.3	0.802
V	2295	16	2	64	17.5	0	144.75	149.27	72.0	8.95	4.52	1.98	147.0	0.796
VI	2297	17	2	64	17.5	0	107.67	109.92	49.5	11.9	2.25	5.29	108.8	0.574
VII	2314	18	3	34	17.5	0	146.15	149.80	96.5	7.09	3.65	1.94	148.0	0.802
VIIa	2315	--	3	34	17.5	0	122.92	125.89	59.4	10.4	2.97	3.50	124.4	0.659
VIIb	2316	--	3	34	17.5	0	116.59	118.79	75.7	8.64	2.20	3.93	117.7	0.634
VIII	2317	19	3	34	17.5	0	111.49	113.78	56.7	10.8	2.29	4.72	112.6	0.596
IX	2321	20	4	0	17.5	0	129.65	131.87	100	6.88	2.22	3.10	130.8	0.686
IXa	2323	--	4	2	17.5	0	139.36	144.96	43.8	13.0	5.60	2.32	142.2	0.755

Table 7. Core Loadings Established With Unit Assemblies

Core	Run	Ldg diagr. Fig. No.	Spacing between assys, pin pitches	Metal separating unit assys	Moder temp, C	Moder boron conc, ppm (±3)	Critical moder ht, cm (±0.2)	Super- critical moder ht, cm (±0.2)	Doubling time, s	$\Delta\rho$, %	ΔH , cm (±0.02)	$\frac{\Delta\rho}{\Delta H}$	$\bar{H}$, cm	$\left(\frac{\Delta\rho}{\Delta H}\right)^{-1/3}$
X	2348	21	3	None	24.5	143	149.12	153.16	77.3	8.50	4.04	2.10	151.1	0.781
XI	2355	22	1	SS	25.5	510	145.86	153.36	36.6	14.8	7.50	1.97	149.6	0.798
XI	2359	22	1	SS	26	514	149.90	153.86	92.4	7.31	3.96	1.85	151.9	0.815
XI	2360	22	1	SS	25.5	501	136.84	141.86	39.8	14.0	5.02	2.79	139.4	0.710
XI	2361	22	1	SS	25	493	130.42	133.71	59.8	10.4	3.29	3.16	132.1	0.681
XI	2362	22	1	SS	25.5	474	118.84	121.44	56.6	10.8	2.60	4.15	120.1	0.622
XI	2363	22	1	SS	25	462	111.58	113.94	52.0	11.5	2.36	4.87	112.8	0.590
XI	2364	22	1	SS	25.5	432	100.89	102.64	48.5	12.0	1.75	6.86	101.8	0.526
XII	2370	23	2	SS	26	217	150.17	152.80	138.3	5.25	2.63	2.00	151.5	0.794
XIII	2378	22	1	B/A1 Set 5	20	15	150.27	155.54	59.5	10.4	5.27	1.97	152.9	0.798
XIIIa	2423	22	1	B/A1 Set 5a	17	28	149.69	153.59	87.8	7.70	3.90	1.97	151.6	0.798
XIV	2384	22	1	B/A1 Set 4	18	92	149.12	153.40	72.0	8.95	4.28	2.09	151.3	0.782
XV	2388	22	1	B/A1 Set 3	18	395	151.45	154.98	134	5.33	3.53	1.51	153.2	0.872
XVI	2396	23	2	B/A1 Set 3	17.5	121	149.16	153.32	95.8	7.13	4.16	1.71	151.2	0.836
XVII	2402	22	1	B/A1 Set 2	17.5	487	149.88	154.36	70.8	9.10	4.48	2.03	152.1	0.790
XVIII	2407	23	2	B/A1 Set 2	18	197	149.02	153.67	65.2	9.70	4.65	2.09	151.3	0.782
XIX	2411	22	1	B/A1 Set 1	17.5	634	149.00	153.41	70.5	9.10	4.41	2.06	151.2	0.786
XX	2414	23	2	B/A1 Set 1	17.5	320	148.10	153.47	52.3	11.4	5.37	2.12	150.8	0.778
XXI	2420	24	3	B/A1 Set 1	16.5	72	151.69	154.19	140.7	5.12	2.50	2.05	152.9	0.787

Table 8. Benchmark Core Loadings Adjusted to 145-cm Moderator Height

Core	Ldg diagr. Fig. No.	Spacing between arrays, pin pitches	No. of B ₄ C pins	Moder boron conc, ppm	Reactivity (ρ) at 145-cm moder ht, ¢	Moder temp, C	Contribution to uncertainty on k_{eff} , $\Delta k/k$		k_{eff} at 145-cm moder height	Combined std dev'n
							From adj to 145 cm moder ht	From uncertainty in moderator boron conc		
I	12	--	0	0	2.5	21	0.0000	0.0005	1.0002	± 0.0005
II	13	0	0	1037	1.6	18.5	0.0000	0.0005	1.0001	± 0.0005
III	14	1	0	764	0.3	18	0.0000	0.0006	1.0000	± 0.0006
IV	15	1	84	0	-1.4	17	0.0000	0.0006	0.9999	± 0.0006
V	16	2	64	0	0.5	17.5	0.0000	0.0007	1.0000	± 0.0007
VI	17	2	64	0	128.6	17.5	0.0010	0.0007	1.0097	± 0.0012
VII	18	3	34	0	-2.4	17.5	0.0000	0.0009	0.9998	± 0.0009
VIII	19	3	34	0	109.7	17.5	0.0009	0.0009	1.0083	± 0.0012
IX	20	4	0	0	40.3	17.5	0.0003	0.0009	1.0030	± 0.0009

Table 9. Benchmark Core Loadings Adjusted to 150-cm Moderator Height

Core	Ldg diag. Fig. No.	Spacing between arrays, pin itches	Type of isolation sheets	Moder B conc, ppm	Reactivity (ρ) at 150-cm moder ht, $\%$	Moder temp, C	Contribution to uncertainty on k_{eff} , $\Delta k/k$			k_{eff} at 150-cm moder height	Combined std dev'n
							From adj to 150 cm moder ht	From uncert. in avg bldg of isol sheets	From uncert. in moder B conc		
X	21	3	None	143	1.9	24.5	0.0000	--	0.0009	1.0001	± 0.0009
XI	22	1	SS	514	0.2	26	0.0000	--	0.0006	1.0000	± 0.0006
XII	23	2	SS	417	-0.4	26	0.0000	--	0.0007	1.0000	± 0.0007
XIII	22	1	1.614% B/A1	15	-0.6	20	0.0000	0.0008	0.0006	1.0000	± 0.0010
XIV	22	1	1.257% B/A1	92	1.9	18	0.0000	0.0008	0.0006	1.0001	± 0.0010
XV	22	1	0.401% B/A1	395	-3.0	18	0.0000	0.0015	0.0006	0.9998	± 0.0016
XVI	23	2	0.401% B/A1	121	1.8	17.5	0.0000	0.0018	0.0007	1.0001	± 0.0019
XVII	22	1	0.242% B/A1	487	0.2	17.5	0.0000	0.0008	0.0006	1.0000	± 0.0010
XVIII	23	2	0.242% B/A1	197	2.1	18	0.0000	0.0009	0.0007	1.0002	± 0.0011
XIX	22	1	0.100% B/A1	634	2.2	17.5	0.0000	0.0008	0.0006	1.0002	± 0.0010
XX	23	2	0.100% B/A1	320	4.1	17.5	0.0000	0.0009	0.0007	1.0003	± 0.0011
XXI	24	3	0.100% B/A1	72	-3.5	16.5	0.0000	0.0012	0.0009	0.9997	± 0.0015

Table 10. Atom Densities of Materials Used in
KENO Model Cores I-IX

Core	Material	Atom	No. densities, atoms/b-cm
All	Fuel	^{235}U	5.67505-4
		^{238}U	2.22265-2
		Oxygen	4.55881-2
All	Aluminum type 6061	Magnesium	5.34873-4
		Aluminum	5.80754-2
		Silicon	4.63000-4
		Chromium	1.09416-4
		Manganese	4.43813-5
		Iron	2.03741-4
		Copper	1.02328-4
IV	Water, 17C	Hydrogen	6.67755-2
		Oxygen	3.33877-2
V-IX	Water, 17.5C	Hydrogen	6.67695-2
		Oxygen	3.33848-2
III	Water, 18C 764 ppm	Hydrogen	6.67635-2
		Oxygen	3.33818-2
		Boron	4.26266-5
II	Water, 18.5C 1037 ppm	Hydrogen	6.67572-2
		Oxygen	3.33786-2
		Boron	5.78529-5
I	Water, 21C	Hydrogen	6.67232-2
		Oxygen	3.33616-2
II-VIII	Boron poison	Boron	5.54982-2
		Carbon	1.33497-2
		Oxygen	3.32183-5

Table 11. Atom Densities of Materials Used in
KENO Model Cores X-XII

Core	Material	Atom	No. densities, atoms/b-cm
X	Water, 24.5C, 143 ppm	Hydrogen	6.66683-2
		Oxygen	3.33342-2
		Boron	7.9672-6
X	Moderator	Water, core X	0.997947*
		Aluminum	1.1922-4
XI	Water, 26C, 514 ppm	Hydrogen	6.66424-2
		Oxygen	3.33212-2
		Boron	2.8626-5
XI	Moderator	Water, core XI	0.997947*
		Aluminum	1.1922-4
XII	Water, 26C, 217 ppm	Hydrogen	6.66424-2
		Oxygen	3.33212-2
		Boron	1.2082-5
XII	Moderator	Water, core XII	0.997947*
		Aluminum	1.1922-4
XI-XII	SS 304	Carbon	2.0124-4
		Manganese	1.4695-3
		Sulfur	1.5078-5
		Silicon	1.0035-3
		Chromium	1.6772-2
		Nickel	6.5966-3
		Molybdenum	6.5504-5
		Copper	5.3252-5
		Iron	6.1838-2

- - - - -
*Multiply this number by the number density of the water
components tabulated directly above, to obtain the number
density of each constituent.

Table 12. Atom Densities for Materials Used in
KENO Model Cores XIII-XXI

Core	Material	Atom	No. densities, atom/b-cm
XIII	Poison plate 5	Boron	2.4368-3
		Aluminum	5.9382-2
		Iron	4.6005-5
		Silicon	3.4304-5
XIV	Poison plate 4	Boron	1.8978-3
		Aluminum	5.9598-2
		Iron	4.6172-5
		Silicon	3.4429-5
XV-XVI	Poison plate 3	Boron	6.0543-4
		Aluminum	6.0115-2
		Iron	4.6572-5
		Silicon	3.4727-5
XVII-XVIII	Poison plate 2	Boron	3.6537-4
		Aluminum	6.0211-2
		Iron	4.6646-5
		Silicon	3.4783-5
XIX-XXI	Poison plate 1	Boron	1.5098-4
		Aluminum	6.0296-2
		Iron	4.6713-5
		Silicon	3.4832-5
XIII	Water, 20C, 15 ppm	Hydrogen	6.67373-2
		Oxygen	3.33687-2
		Boron	8.36585-7
XIII	Moderator	Water, core XIII	0.997947*
		Aluminum	1.1922-4
XIV	Water, 18C, 92 ppm	Hydrogen	6.67635-2
		Oxygen	3.33813-2
		Boron	5.1331-6
XIV	Moderator	Water, core XIV	0.997947*
		Aluminum	1.1922-4
XV	Water, 18C, 395 ppm	Hydrogen	6.67635-2
		Oxygen	3.33818-2
		Boron	2.2039-5
XV	Moderator	Water, core XV	0.997947*
		Aluminum	1.1922-4
XVI	Water, 17.5C, 121 ppm	Hydrogen	6.67695-2
		Oxygen	3.33848-2
		Boron	6.7517-6
XVI	Moderator	Water, core XVI	0.997947*
		Aluminum	1.1922-4

Table 12. (Cont'd)

<u>Core</u>	<u>Material</u>	<u>Atom</u>	<u>No. densities, atom/b-cm</u>
XVII	Water, 17.5C, 487 ppm	Hydrogen	6.67695-2
		Oxygen	3.33848-2
		Boron	2.7174-5
XVII	Moderator	Water, core XVII	0.997947*
		Aluminum	1.1922-4
XVIII	Water, 18C, 197 ppm	Hydrogen	6.67635-2
		Oxygen	3.33818-2
		Boron	1.0991-5
XVIII	Moderator	Water, core XVIII	0.997947*
		Aluminum	1.1922-4
XIX	Water, 17.5C, 634 ppm	Hydrogen	6.67695-2
		Oxygen	3.33848-2
		Boron	3.5377-5
XIX	Moderator	Water, core XIX	0.997947*
		Aluminum	1.1922-4
XX	Water, 17.5C, 320 ppm	Hydrogen	6.67695-2
		Oxygen	3.33848-2
		Boron	1.7856-5
XX	Moderator	Water, core XX	0.997947*
		Aluminum	1.1922-4
XXI	Water, 16.5C, 72 ppm	Hydrogen	6.67812-2
		Oxygen	3.33906-2
		Boron	4.0183-6
XXI	Moderator	Water, core XXI	0.997947*
		Aluminum	1.1922-4

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*Multiply this number by the number density of the water components tabulated directly above, to obtain the number density of each constituent.

Table 13. Results of KENO Analysis
of Benchmark Cores

<u>Core</u>	<u>k_{eff} calculated by KENO ($\pm 1 \sigma$)</u>
I	0.998 $\pm$ 0.006
II	1.007 $\pm$ 0.004
III	0.999 $\pm$ 0.004
IV	1.004 $\pm$ 0.007
V	1.005 $\pm$ 0.005
VI	0.998 $\pm$ 0.004
VII	0.994 $\pm$ 0.005
VIII	1.003 $\pm$ 0.005
IX	0.987 $\pm$ 0.005
X	0.988 $\pm$ 0.004
XI	1.015 $\pm$ 0.004
XII	0.991 $\pm$ 0.005
XIII	1.008 $\pm$ 0.005
XIV	1.003 $\pm$ 0.004
XV	0.995 $\pm$ 0.005
XVI	0.990 $\pm$ 0.005
XVII	0.993 $\pm$ 0.005
XVIII	1.005 $\pm$ 0.005
XIX	0.991 $\pm$ 0.004
XX	0.997 $\pm$ 0.005
XXI	0.981 $\pm$ 0.004

Table 14. Results of PDQ Analysis
of Selected Cores

<u>Core</u>	<u>PDQ-7</u>	<u>Experimental</u>
III	0.9931	1.0000
VI	0.9284	1.0097
IX	1.0103	1.0030

Table 15. Measured Vs Calculated Values of k_{eff}

<u>Spacing between arrays, inches</u>	<u>Core</u>	<u>Calculated by KENO</u>	<u>Measured</u>	<u>Calculated minus measured</u>
None	I	0.998±0.006	1.0002±0.0005	-0.002
	II	1.007±0.004	1.0001±0.0005	+0.007
0.644	III	0.999±0.004	1.0000±0.0006	-0.001
	IV	1.004±0.007	0.9999±0.0006	+0.004
	XI	1.015±0.004	1.0000±0.0006	+0.015
	XIII	1.008±0.005	1.0000±0.0010	+0.008
	XIV	1.003±0.004	1.0001±0.0010	+0.003
	XV	0.995±0.005	0.9998±0.0016	-0.005
	XVII	0.993±0.005	1.0000±0.0010	-0.007
	XIX	0.991±0.004	1.0002±0.0010	-0.009
1.288	V	1.005±0.005	1.0000±0.0007	+0.005
	VI	0.998±0.004	1.0097±0.0012	-0.012
	XII	0.991±0.005	1.0000±0.0007	-0.009
	XVI	0.990±0.005	1.0001±0.0019	-0.010
	XVIII	1.005±0.005	1.0002±0.0011	+0.005
	XX	0.997±0.005	1.0003±0.0011	-0.003
1.932	VII	0.994±0.005	0.9998±0.0009	-0.006
	VIII	1.003±0.005	1.0083±0.0012	-0.005
	X	0.988±0.004	1.0001±0.0009	-0.012
	XXI	0.981±0.004	0.9997±0.0015	-0.019
2.576	IX	0.987±0.005	1.0030±0.0009	-0.016

Figure 1. Vertical Section Through Core Tank

Figure 2. Moderator Fill System

Figure 3. Dimensions of 2.46%-Enriched UO_2 Fuel Rod

Note: All dimensions in centimeters.

Figure 4. Partially Loaded Unit Assembly

Figure 5. Typical Core Utilizing Large
Top and Bottom Grids

Figure 6. Vertical Dimensions, Cores I-IX

Figure 7. Typical Core Comprised of Unit Assemblies
and Isolation Sheets

Figure 8. Vertical Dimensions, Cores X-XXI

Note: Dimensions given in centimeters.

Figure 9. Isometric View of Cores Comprised of Unit Assemblies and Isolation Sheets

Figure 10. Lynchburg Pool Reactor

Figure 11. Location of Sampling Points on Borated Aluminum Sheets

Figure 12. Core I Loading Diagram — Cylindrical
Base Case

Fuel Rod Position

Figure 13. Core II Loading Diagram — Nine Arrays
With Zero Pin Pitch Separation

□ Fuel Rod Position

Figure 14. Core III Loading Diagram — Nine Arrays
Separated by One Pin Pitch

□ Fuel Rod Position

Figure 15. Core IV Loading Diagram — Nine
Arrays Separated by One Pin
Pitch and 84 B_4C Pins

- Fuel Rod Position
- B_4C Pin

Figure 16. Core V Loading Diagram — Nine
Arrays Separated by Two Pin
Pitches and 64 B₄C Pins

- Fuel Rod Position
- B₄C Pin

Figure 17. Core VI Loading Diagram — Nine
Arrays Separated by Two Pin
Pitches and 64 B₄C Pins

- Fuel Rod Position
- B₄C Pin

Figure 18. Core VII Loading Diagram — Nine
Arrays Separated by Three Pin
Pitches and 34 B_4C Pins

- Fuel Rod Position
- B_4C Pin

Figure 19. Core VIII Loading Diagram — Nine
Arrays Separated by Three Pin
Pitches and 34 B₄C Pins

- Fuel Rod Position
- B₄C Pin

Figure 20. Core IX Loading Diagram — Nine
Arrays Separated by Four Pin
Pitches

□ Fuel Rod Position

Figure 21. Core X Loading Diagram — Nine
Unit Assemblies Separated by
Three Pin Pitches

- Fuel Rod Position
- Threaded Aluminum Rod

Figure 22. Cores XI, XIII, XIV, XV, XVII, and XIX —
Nine Unit Assemblies Separated by One
Pin Pitch and Metal Isolation Sheets

- Fuel Rod Position
- Threaded Aluminum Rod
- Isolation Sheet

Figure 23. Cores XII, XVI, XVIII, and XX — Nine Unit Assemblies Separated by Three Pin Pitches and Metal Isolation Sheets

- Fuel Rod Position
- Threaded Aluminum Rod
- Isolation Sheet

Figure 24. Core XXI — Nine Unit Assemblies
Separated by Three Pin Pitches
and Metal Isolation Sheets

- Fuel rod Position
- Threaded Aluminum Rod
- Isolation Sheet

Figure 25. $(d\rho/dH)^{-1/3}$ Vs Moderator Height

Figure 26. Excess Reactivity to 145 cm Vs Moderator Height — Cores I-IX

Figure 27. Excess Reactivity to 150 cm Vs Moderator Height — Cores X-XXI

Figure 28. Moderator Boron Concentration Vs Boron Content
of Isolation Sheets for Critical Core

Figure 29. KENO Model of DOE Critical Experiments

Figure 30. Core I k_{eff} as Function of Initial Generations Skipped - 60 Generations

Figure 31. Core II k_{eff} as Function of Initial Generations
Skipped - 60 Generations

Figure 32. Core III k_{eff} as Function of Initial Generations
Skipped - 60 Generations

Figure 33. Core IV k_{eff} as Function of Initial Generations
Skipped — 60 Generations

Figure 34. Core V k_{eff} as Function of Initial Generations Skipped - 60 Generations

Figure 35. Core VI k_{eff} as Function of Initial Generation Skipped - 90 Generations

Figure 36. Core VII k_{eff} as Function of Initial Generations
Skipped - 60 Generations

Figure 37. Core VIII k_{eff} as Function of Initial Generations
Skipped - 60 Generations

Figure 38. Core IX k_{eff} as Function of Initial Generations Skipped - 56 Generations

Figure 39. Core X k_{eff} as Function of Initial Generations Skipped - 90 Generations

Figure 40. Core XI k_{eff} as Function of Initial Generations Skipped — 60 Generations

Figure 41. Core XII k_{eff} as Function of Initial Generations Skipped - 75 Generations

Figure 42. Core XIII k_{eff} as Function of Initial Generations
Skipped - 60 Generations

Figure 43. Core XIV k_{eff} as Function of Initial Generations Skipped — 90 Generations

Figure 44. Core XV k_{eff} as Function of Initial Generations Skipped — 60 Generations

Figure 45. Core XVI k_{eff} as Function of Initial Generations Skipped — 90 Generations

Figure 46. Core XVII k_{eff} as Function of Initial Generations
Skipped - 60 Generations

Figure 47. Core XVIII k_{eff} as Function of Initial Generations
Skipped - 60 Generations

Figure 48. Core XIX k_{eff} as Function of Initial Generations Skipped — 90 Generations

Figure 49. Core XX k_{eff} as Function of Initial Generations
Skipped - 60 Generations

Figure 50. Core XXI k_{eff} Function of Initial Generations
Skipped - 86 Generations

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APPENDIX A
Measured Boron Distribution Through
Borated Isolation Sheets

Table A-1. Borated Aluminum Set 1 — Point-wise Boron Variation

Point	Dev'n from set avg, wt % natural B	
	Sheet 1 A	Sheet 1 B
1/6/11	+0.026/-0.014/-0.005	+0.011/-0.009/-0.001
2/7/12	+0.013/-0.014/-0.009	-0.009/-0.020/-0.009
3/8/13	+0.032/-0.022/-0.011	-0.014/-0.018/-0.009
4/9/14	-0.003/-0.034/-0.018	-0.018/-0.011/-0.011
5/10/15	-0.009/-0.027/-0.003	-0.014/-0.031/-0.022
Point	Dev'n from set avg, wt % natural B	
	Sheet 1 C	Sheet 1 D
1/6/11	+0.008/+0.002/+0.006	+0.002/+0.015/+0.030
2/7/12	+0.002/-0.001/+0.002	+0.006/+0.017/+0.019
3/8/13	+0.006/-0.001/+0.006	+0.006/+0.022/+0.011
4/9/14	+0.013/+0.000/-0.011	+0.011/+0.010/+0.013
5/10/15	+0.010/-0.016/-0.007	+0.017/+0.017/+0.019

Table A-2. Borated Aluminum Set 2 — Point-wise Boron Variation

Point	Dev'n from set avg, wt % natural B	
	Sheet 2 A	Sheet 2 B
1/6/11	+0.012/+0.003/-0.024	+0.027/+0.023/-0.021
2/7/12	+0.011/+0.012/-0.028	+0.029/-0.002/-0.028
3/8/13	+0.020/+0.025/-0.037	+0.022/-0.021/-0.030
4/9/14	+0.023/+0.014/-0.048	+0.018/-0.004/-0.028
5/10/15	+0.040/-0.017/-0.039	+0.007/+0.023/-0.043
Point	Dev'n from set avg, wt % natural B	
	Sheet 2 C	Sheet 2 D
1/6/11	-0.020/-0.010/+0.003	+0.007/-0.011/-0.002
2/7/12	-0.017/-0.013/+0.007	+0.009/-0.004/-0.002
3/8/13	-0.015/+0.005/-0.002	-0.006/+0.009/+0.011
4/9/14	-0.008/+0.012/+0.007	+0.001/-0.015/+0.018
5/10/15	-0.008/+0.003/+0.029	-0.017/+0.031/+0.022

Table A-3. Borated Aluminum Set 3 - Point-wise Boron Variation

Point	Dev'n from set avg, wt % natural B	
	Sheet 3 A	Sheet 3 B
1/6/11	+0.005/+0.197/+0.057	+0.098/+0.152/-0.028
2/7/12	+0.013/+0.100/-0.040	+0.124/+0.139/-0.019
3/8/13	+0.031/+0.024/-0.044	+0.153/+0.232/-0.059
4/9/14	+0.038/+0.044/-0.042	+0.144/+0.272/-0.033
5/10/15	+0.058/+0.022/-0.084	+0.135/+0.245/-0.004
Point	Dev'n from set avg, wt % natural B	
	Sheet 3 C	Sheet 3 D
1/6/11	-0.148/-0.139/-0.066	-0.066/-0.050/+0.186
2/7/12	-0.161/-0.170/-0.035	-0.114/-0.165/+0.020
3/8/13	-0.163/-0.172/+0.084	-0.134/-0.123/-0.101
4/9/14	-0.105/-0.086/-0.033	-0.123/-0.037/-0.110
5/10/15	-0.139/-0.137/-0.037	+0.040/+0.253/+0.077

Table A-4. Borated Aluminum Set 4 - Point-wise Boron Variation

Point	Dev'n from set avg, wt % natural B	
	Sheet 4 A	Sheet 4 B
1/6/11	+0.020/+0.068/-0.069	+0.114/+0.070/-0.058
2/7/12	+0.050/+0.004/-0.062	+0.145/+0.081/-0.122
3/8/13	+0.051/-0.040/-0.150	+0.174/+0.066/-0.064
4/9/14	+0.008/+0.002/-0.130	+0.094/+0.110/-0.022
5/10/15	+0.015/-0.036/-0.086	+0.053/+0.192/-0.106
Point	Dev'n from set avg, wt % natural B	
	Sheet 4 C	Sheet 4 D
1/6/11	-0.031/+0.002/-0.018	-0.055/+0.013/+0.002
2/7/12	-0.014/+0.000/-0.055	+0.011/-0.038/-0.007
3/8/13	-0.078/+0.072/-0.042	-0.038/+0.000/-0.099
4/9/14	-0.016/+0.114/+0.050	-0.073/+0.022/-0.082
5/10/15	-0.011/+0.110/+0.000	-0.069/+0.051/-0.099

Table A-5. Borated Aluminum Set 5 — Point-wise Boron Variation

Point	Dev'n from set avg, wt % natural B	
	Sheet 5 A	Sheet 5 B
1/6/11	+0.071/+0.048/+0.152	-0.066/+0.114/+0.059
2/7/12	+0.103/+0.013/-0.024	-0.121/+0.115/+0.103
3/8/13	+0.097/+0.022/+0.011	-0.027/+0.170/+0.106
4/9/14	+0.079/+0.079/+0.095	-0.038/+0.126/+0.220
5/10/15	+0.110/+0.060/+0.123	+0.037/+0.104/+0.163
Point	Dev'n from set avg, wt % natural B	
	Sheet 5 C	Sheet 5 D
1/6/11	-0.104/-0.115/-0.245	-0.159/+0.029/+0.044
2/7/12	-0.113/-0.139/-0.223	-0.223/+0.020/+0.020
3/8/13	-0.040/-0.059/-0.115	-0.192/+0.071/-0.002
4/9/14	+0.183/-0.024/-0.069	-0.183/-0.004/-0.106
5/10/15	-0.059/+0.055/+0.024	-0.185/-0.124/-0.115

Table A-6. Borated Aluminum Set 5 — Point-wise Boron Variation

Point	Dev'n from set avg, wt % natural B	
	Sheet 5 A	Sheet 5 B
1/6/11	+0.044/+0.027/-0.037	-0.011/-0.124/+0.229
2/7/12	-0.027/+0.013/+0.059	+0.062/-0.066/-0.004
3/8/13	-0.174/-0.188/-0.068	-0.073/+0.009/+0.073
4/9/14	-0.066/-0.123/+0.040	-0.044/+0.119/+0.703
5/10/15	-0.130/-0.042/+0.165	+0.015/+0.223/+0.240
Point	Dev'n from set avg, wt % natural B	
	Sheet 5 C	Sheet 5 D
1/6/11	-0.027/-0.011/-0.157	+0.053/+0.135/-0.055
2/7/12	+0.013/+0.015/-0.057	-0.035/-0.073/-0.165
3/8/13	+0.207/+0.002/+0.124	-0.168/-0.070/-0.143
4/9/14	+0.176/+0.064/-0.016	-0.073/-0.112/-0.099
5/10/15	+0.018/+0.015/-0.112	-0.130/-0.016/-0.119

APPENDIX B
Input-Output Listing of Computer Calculations

Microfiche copies of the following input-output listings are contained in an envelope at the back of this report.

<u>Description</u>	<u>ID No.</u>
NITAWL for all KENO Runs	NITC461
Core I KENO run	DOEC40S
Core II KENO run	DOEC49S
Core III KENO run	DOEC40R
Core IV KENO run	DOEC40N
Core V KENO run	DOEC40M
Core VI KENO run	DOEC47H
Core VII KENO run	DOEC40K
Core VIII KENO run	DOEC40L
Core IX KENO run	DOEC40D
Core X KENO run	DOEC40C
Core XI KENO run	DOEC4N8
Core XII KENO run	DOEC40A
Core XIII KENO run	DOEC4N6
Core XIV KENO run	DOEC47J
Core XV KENO run	DOEC4N2
Core XVI KENO run	DOEC4NT
Core XVII KENO run	DOEC4NU
Core XVIII KENO run	DOEC4MQ
Core XIX KENO run	DOEC4MU
Core XX KENO run	DOEC47R
Core XXI KENO run	DOEC4MK
Core III PDQ run	PDQC4I6
Core VI PDQ run	PDQC4JB
Core IX PDQ run	PDQC4I8

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