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BORAX V EXPONENTIAL EXPERIMENT

by

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I. SUMMARY

The cadmium ratio was measured in an exponential mockup of BORAX V as a function of the void fraction. The extent of voids, simulated by lengths of closed polyethylene tubes, ranged from 0% to 40%. The corresponding cadmium ratios ranged from 6.1 to 4.6. The exponential was also used to determine the radial flux pattern across a BORAX-type fuel assembly and the fine flux detail in and around fuel rods. For a normal loading the maximum-to-average power generation across an assembly was 1.24.

II. INTRODUCTION

One of the parameters to be investigated in the BORAX V experimental program is that of void formation and its effect on reactivity, stability, and problems of heat transfer. The importance of this parameter can be judged by the large amount of reactivity held by the voids and the fact that void formation (or, more accurately, formation of steam bubbles) is the mechanism that gives the boiling water reactor its principal shutdown mechanism.

Of the various approaches used by others to measure voids, the technique proposed by S. Untermeyer and tried by J. A. Thie et al,[1] seemed to be the most satisfactory for our purposes. In this method, the rather localized formation of voids in a particular region is associated with a change in the ratio of epithermal neutron flux to thermal flux in that region. This change in ratio can be deduced from a measured change in the cadmium ratio.

Thie used this technique for measuring the distribution of voids in EBWR. He was able to show that the cadmium ratio did change as a function of vertical distance along a boiling channel and, in general, could be correlated to the variation in steam formation.

Therefore, an exponential mockup assembly of BORAX V was built to explore the cadmium-ratio technique of measuring voids and, by using known void fractions, to prepare a calibration curve for BORAX V. Other worthwhile measurements to implement the BORAX V experimental program were performed. A summary of the proposed exponential program follows:

a. Calibrate the actual cadmium ratio with a known void fraction under the conditions of measurement actually to be used in BORAX V and estimate how localized is the effect of the void on the cadmium ratio.

b. Make radial flux measurements across a typical BORAX V fuel assembly, investigating the flux-flattening effect of poison rods and of 9.9% U^{235} enriched fuel rods.

c. Investigate some of the nuclear parameters of BORAX V, where applicable, as well as the exponential.

d. Check out the data-logging equipment proposed for use in the BORAX V program. Both the mechanical and electronic sections were to be tested and necessary changes made before the equipment would be installed at BORAX V.

III. EXPERIMENTAL EQUIPMENT

A. Exponential Assembly

The exponential assembly was built to match as closely as possible the physical dimensions and material composition to be found in a clean BORAX V.[2] The fundamental unit is the fuel-element subassembly, which is essentially a 4 in. x 4 in. aluminum box with 49 fuel elements positioned on $\frac{1}{2}$-in. centers in a square array. Grid plates at top and bottom hold the elements in position. When these subassemblies are loaded into BORAX, each group of four is surrounded by a $\frac{1}{2}$-in. control rod channel which is either filled with control rods or aluminum followers of the same dimensions. For the exponential loading, the control rod channels were eliminated, but the composition of the individual subassembly was retained.

The exponential assembly was horizontal and mocked up nine of the BORAX V subassemblies. The nine subassembly mockups were divided into three trays of three each. The amount of aluminum in the trays and end-support plates gave the same metal-to-moderator-to-fuel ratios per subassembly as occurs in BORAX V. The three trays were placed in an aluminum tank large enough to give a minimum of $\frac{3}{4}$ in. of water around the entire assembly.

From theoretical and experimental work, it was decided (see Appendix) to limit the size of the assembly to a maximum of 349 fuel elements surrounded by a layer of 20-mil cadmium. This was accomplished by riveting sheets of cadmium on aluminum frames and fixing these in the appropriate positions in each fuel subassembly.

Fill, drain, and overflow lines were provided to the tank. Also, a provision was made for a counter to be placed adjacent to the periphery of the assembly in order to monitor neutron fluxes.

Provisions were made to load the detectors along the axis of the assembly in several radial positions. The detectors could be removed after an irradiation without unloading the assembly, thereby reducing exposure of personnel to radiation, as well as time lost between irradiation and counting. Figure 1 shows the assembly loaded with the middle and lower tray of elements. Figure 2 shows the top tray with the cadmium sheet in place. Figure 3 is a view of assembly just prior to inserting the exponential experiment into the TREAT access hole.

Fig. 1. Assembly View Showing Middle Tray of Elements

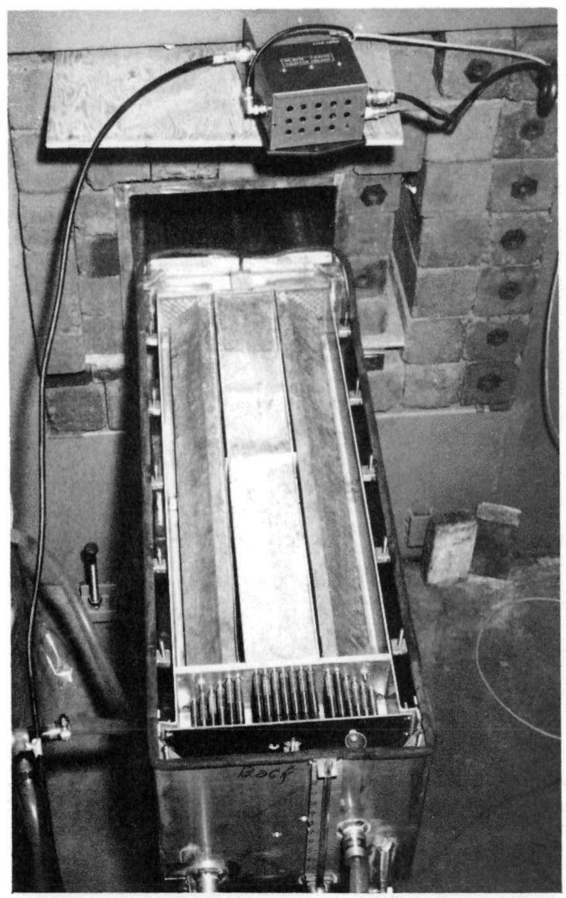

Fig. 2. Assembly View Showing Completed Assembly and Surrounding Cadmium Sheath

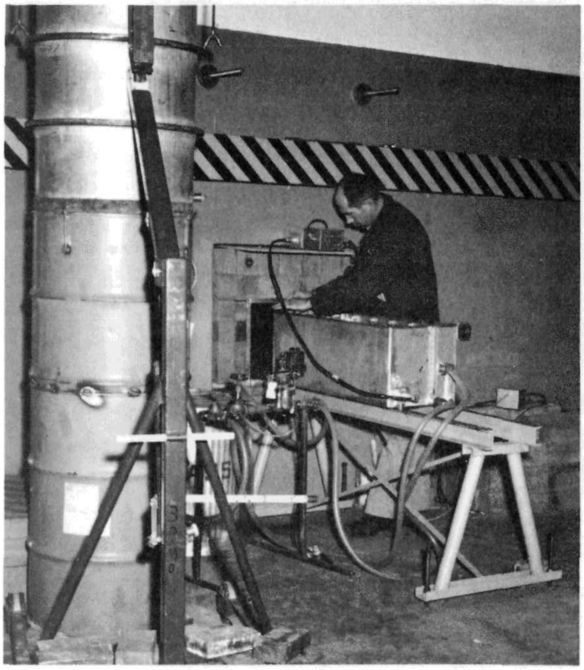

Fig. 3. View of Assembly Just Prior to Insertion into Source (TREAT)

B. Neutron Source: TREAT

The TREAT Reactor(3) was used to provide the neutron source for the exponential assembly. An aluminum liner was fabricated to fit into one of the access holes as shown in the Figs. 1 through 3. The liner butted up against the permanent reflector of the reactor. Raising the movable reflector block formed a truncated neutron collimator, 15 in. high by 4 in. wide at the reactor core and 15 in. square at the exponential assembly.

Rails were provided in the liner and outside the reactor to permit rolling the exponential assembly into and out of position for irradiation or loading changes. A plan view of the reactor and the assembly is shown in Fig. 4.

C. Detectors and Associated Equipment

1. Detectors

The principal variable to be measured was neutron flux; the detector was of U^{235} in the form of a wire, composed of a 96.62 w/o Zr and 3.38 w/o U^{235} alloy. This wire had been quality-made for uniformity and homogeneity. For most measurements in the exponential assembly, the wire was snipped into $\frac{3}{8}$-in. lengths and weighed. After discarding a few bad segments, the detectors were of uniform weight to within $\pm\frac{1}{2}$%.

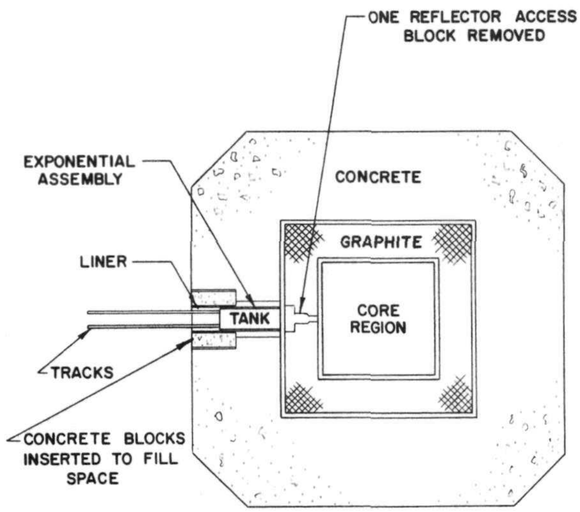

Fig. 4. Plan View of BORAX V Experiment as Installed in TREAT

Full-length (~ 32 in.) wires of the zirconium alloy and uranium wires containing 93% U^{235} were also available for use in running the traverses. As will be explained later, they were used as a checkout of the wire counter equipment only.

2. Cadmium Sheath

For measurement of the cadmium ratio, tubes of 20-mil-thick cadmium were obtained, 35 mil ID x 75 mil OD. These tubes were in lengths up to 36 in. long.

3. Counting Equipment

For detection of the activity of the flux detectors, three independent β-sensitive scintillation counters were used. These were 3-mm anthracene crystals mounted on RCA photomultiplier tubes. Standard preamplifiers, scalers, and power supply completed the basic counting system. Three setups were needed in order to count the bare and the cadmium-covered wires simultaneously along with a monitor wire which operated a preset counter to compensate automatically for the activity decay of the detectors. It was necessary to count as soon after irradiation as possible to make use of the high counting rate without excessively high irradiation. Care had to be taken that the three setups had the same β-sensitivity so that one could assume the same decay scheme rate for all of them.

Separate high-voltage and pulse-height discriminator curves were run with the three setups, using β sources of different energies as well as a Co^{60} gamma source.

Appropriate settings of the high voltage and discriminators gave reasonably equal sensitivities with about 15% of the counts coming from gammas. It was unfortunate that, for sensitivity reasons, it was necessary to count the wires so soon after irradiation, during which time the decay spectrum was changing rather rapidly. It was possible to detect a small change in the relative sensitivity among the three setups during the beginning and end of the run. When necessary, corrections were made to the data.

The photomultiplier and crystal were shielded by mounting them inside open-ended lead pigs.

The wire samples were placed in a wire holder approximately $\frac{7}{16}$ in. above the crystal. The reproducibility of position was well within normal counting statistics. The limited life of the program obviated the need of remote operation of the equipment, other than controlling the counting time with the preset scaler.

4. Automatic Wire Counter

An automatic wire scanner (see Fig. 5) had been designed for data acquisition on the BORAX V project. Initially, long wires were irradiated in the TREAT core and also in the exponential assembly to try out the systems and to determine the feasibility of the experiment. Basically, with a few modifications, the wire counter worked with the exponential assembly; however, the geometry of the system was such that radiations of the order of 40 times greater would have been needed for adequate counting statistics. The individual wire segments arranged in a better counting geometry were used to overcome this deficiency. The wire-counting equipment is being used in the regular BORAX program.

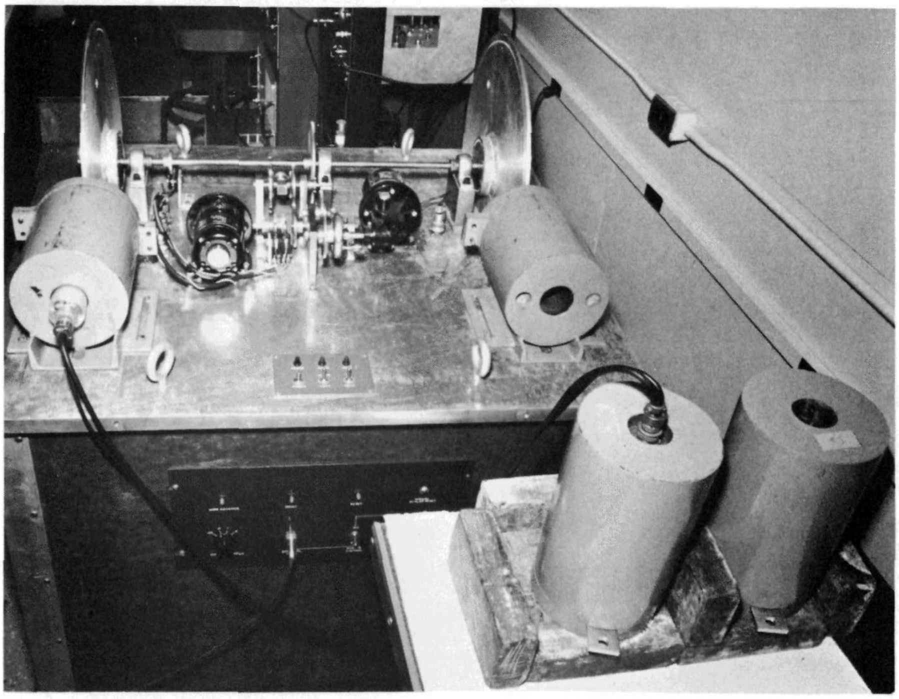

Fig. 5. Wire-counting Equipment

D. Void Tubes

To simulate voids, sealed polyethylene tubes of the appropriate length and number were placed between the fuel elements of the assembly. Void fractions were calculated on the basic cell of a $\frac{1}{2}$-in. square as follows:

$$\% \text{ Void} = \frac{N[\pi(ID)/2]^2\ 100}{(\frac{1}{2})^2 - (\pi R^2)} ,$$

where N is the number of void tubes in a channel, ID the inside diameter of the polyethylene tubes, and R the radius of fuel rod. From this it can be seen that the extra water around the outer row of fuel rods in a sub-assembly was neglected, since it was expected that the void effect would be fairly localized around the region of measurement. The polyethylene tubes are of a commercial product called "Flexite." Table I lists the sizes used for these experiments and the void fractions obtainable. Table II lists the impurities present as determined by a mass spectrograph. For these experiments, the polyethylene was considered equivalent to water.

Table I

POLYETHYLENE TUBE SIZES AND VOID FRACTIONS PER TUBE

Size	ID (in.)	Wall (in.)	%Void
12	0.085	0.016	4.05
10	0.106	0.016	6.3
8	0.133	0.020	9.9
5	0.186	0.020	19.5
1	0.294	0.020	48.0

Table II

IMPURITIES PRESENT IN POLYETHYLENE

Metal	ppm	Metal	ppm
Al	100	Mg	400
Ca	400	Mn	10
Cr	10	Si	20
Fe	100		

The tubes were sealed in appropriate lengths by heating the ends to the melting point and gently twisting and pulling. A spot check of the average ID of a bundle of these tubes was made by determining the amount of liquid necessary to fill the tubes to a known height. This measurement agreed with the nominal ID as given in Table I.

E. Associated Equipment

The exponential assembly was filled with water by gravity flow through an orifice which limited the rate of fill to ~$\frac{1}{2}$ in./min. A 55-gal stainless steel drum was filled with demineralized water and hoisted above the level of the exponential assembly. For draining, the drum was set on the floor and the tank emptied at a more rapid rate than the fill rate. A water can was provided for overflow. Approximate times for filling and draining were 30 and 5 min, respectively.

A BF_3 counter was mounted in one corner of the exponential assembly (inside the cadmium shield, but outside the fuel rods) to monitor changes in neutron flux resulting from changes made in the assembly. It was also used to measure the changes in neutron multiplication during the initial loading.

F. Fuel

The assembly used the same fuel rods that were fabricated for BORAX V.(2) Of the 6000 elements made for BORAX V, 349 were borrowed for the exponential experiment. The recall of this fuel as BORAX V was loaded to its full complement of 60 subassemblies put a time limit on the exponential program. Eight 9.9% enriched uranium elements, a boron-loaded element, and a hollow aluminum element were also available for the experiment in addition to the regular 4.95% enriched uranium fuel.

IV. EXPERIMENTAL PROCEDURES

A. Initial Loading of the Exponential

Before loading elements in the tank, a $\frac{3}{16}$-in.-diameter fission counter was placed in the central fuel position. This was in addition to the BF_3 counter mounted on one corner of the exponential assembly. The tank was filled with water and the count rate determined by the two counters as a function of the TREAT reactor power.

The first loading was 100 elements, the second 50 elements, and each succeeding loading 25 elements until the assembly was completed. After each fuel addition and with the assembly in place, but before any water was added, the TREAT reactor was brought to power to provide the neutron source. Count rates were taken at several water levels. During the addition of water, the count rate was continuously monitored audibly.

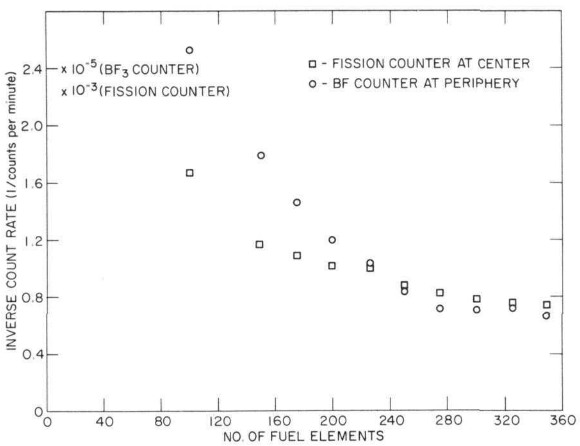

Fig. 6. Inverse Count Rate vs Number of Fuel Elements

The inverse count rate plot for both counters with the full tank of water is given in Fig. 6. By extrapolation of the curve, the estimated number of elements for a critical assembly was found to be somewhere between 800 and 1000 elements. This is a very large extrapolation and should be treated as such.

After having loaded to a full 348 elements, the counter at the center was removed and replaced with a fuel element, giving the fully loaded exponential assembly of 349 elements. It was estimated that the assembly ran at a power level of about 10^{-5} watt/watt of TREAT power.

B. Flux Measurements

Because of the limited time available to complete the experiments, all investigation was limited to the central fuel subassembly and to the reproduction of actual measuring conditions in BORAX V, rather than to perform what might have been cleaner experiments.

The wire segments were loaded in sequence into the cadmium tube pinched together at one end. From 25-50 segments were used. The cadmium tubes were then inserted into a $\frac{1}{8}$-in.-OD stainless steel thimble with a 20-mil-thick wall, the same type as used in BORAX. The original plan was to load the bare wires in a similar thimble to be irradiated at an equal flux position simultaneously with the cadmium wire, but, when it became necessary to use the segmented wire pieces, it was obvious that they could not be loaded into the large-diameter thimble with any hope of keeping them properly positioned. Consequently, they were loaded first into a 15-mil-wall stainless steel capillary tube with a 35-mil ID; this tube subsequently was loaded into the thimble.

The cadmium-covered and uncovered detectors were then irradiated simultaneously at the equivalent radial positions. It should be emphasized that the cadmium ratio and results reported in this paper were the result of experiments performed under conditions as described and would be applicable to BORAX V under the same conditions of measurement.

A preliminary irradiation of the wires was made and the region over which the spectrum was stable determined by plotting the count rate vs distance on log paper and noting the region of pure exponential fall-off. Subsequent irradiations took advantage of the exponential region only.

Extreme care was taken while loading the thimbles to assure accurate positioning of the detectors with respect to the assembly and to each other. The zero position was fixed at the reactor side of the front support plate. The thimbles themselves extended back through the assembly and through rubber-stoppered seals at the rear of the tank. This allowed the wires to be removed from the assembly almost immediately after exposure. In the case of radial traverses, the whole assembly had to be unloaded, necessitating longer waiting periods after irradiation and special techniques to reduce personnel exposure.

In making radial traverses, the flux at the center of each coolant channel under consideration was measured by mounting a wire segment in a Lucite holder which accurately positioned the foil between the four neighboring fuel rods (see Fig. 7). Though care was exercised in lining up the wires in a plane perpendicular to the axis of the assembly, the uncertainty in position was $\pm\frac{1}{4}$ in. The same holder was modified to accept the cadmium-covered wires. In this case, the wires were enclosed in a short length of cadmium tubing pinched at both ends.

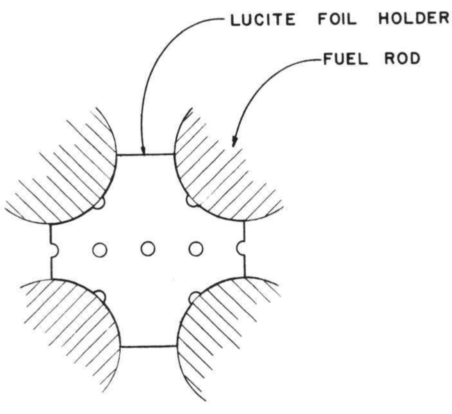

Fig. 7. Holder for Detectors Exposed in Water Channels

For a standard irradiation, TREAT was operated at 67 kw for 1200 sec. This corresponded to something like an energy release of 800 watt-sec in the central fuel subassembly of the exponential assembly. Counting of the foils usually began within 20 min of shutdown time.

Wire segments were unloaded from the rods in sequence. The monitor foil was placed in the third counting setup and operated the preset counter. Corresponding bare and cadmium wire segments were counted simultaneously in the other two counting geometries. By switching foils between the two geometries periodically, the relative sensitivity could be determined. No attempt was made to normalize one run with another, since only relative cadmium ratios were desired.

The count rate vs position was plotted on semi-log paper over the region where the expected straight line relationship was established, since the data were meaningful only for an equilibrium spectrum. The slopes of the two curves (corresponding to the cadmium-covered and bare wires) should be the same.

C. Void Placement

The mocking-up of steam voids in a static system poses a variety of questions; in this case, however, three were particularly significant:

(1) How localized is the void perturbation; or, stated in another way, how does the placing of voids or material close to the detector affect the flux measured by the detector?;

(2) What is the streaming effect if the voids are simulated by hollow tubes 6 to 10 in. long?; and

(3) Can the measurement of a large voided region of known void fraction be applicable to a boiling water reactor when the void fraction is continuously changing?

With these questions in mind, the voids were mocked up as explained in Table III and shown in Fig. 8. For Runs No. 2-4, No. 12 tubing was used in 15-in. lengths. For Runs No. 5, 6, and 8, No. 8 tubing was used with the voids beginning $7\frac{1}{2}$ in. behind the front of the assembly, leaving the unvoided region at the front. The axial measurements then began $4\frac{1}{2}$ in. in front of the void region and extended $4\frac{1}{2}$ in. into the voided region. Run No. 7 was an attempt to mock up an axial variation in voids going from 0% - 10% - 20% - 30% - 40% over lengths of approximately $3\frac{1}{2}$ in. each. Void tubes of 20% and 10% were coupled as shown in Fig. 8f. The 10% void began about 5 in. behind the front of the assembly.

Table III

CADMIUM RATIOS FOR VARIOUS VOID FRACTIONS AND VOID ARRANGEMENTS

Run No.	Void %	Cadmium Ratio	Void Arrangement (see Fig. 10)	Remarks	Fig. No.
1	0	6.1			10
2	4	5.9	a	Void tubes 15 in. long; for full length of measuring region	11
3	8	5.73	b		12
4	16	5.38	c	Void tubes clustered in water channel	13
5	40	6.1/4.64	d	Tubes extend from $7\frac{1}{2}$-15 in. only. Unvoided region from 0-$7\frac{1}{2}$ in.	14
6	40	5.4/4.25	e	Cadmium ratio measured in central fuel position	15
7	0-40	6.1/5.48/5.17	f	Five (5) regions each about $3\frac{1}{2}$ in. long ranging in voids of 0, 10, 20, 30, and 40%	16
8	20	6.28/5.4		Central fuel position contains an aluminum rod filled with water	17

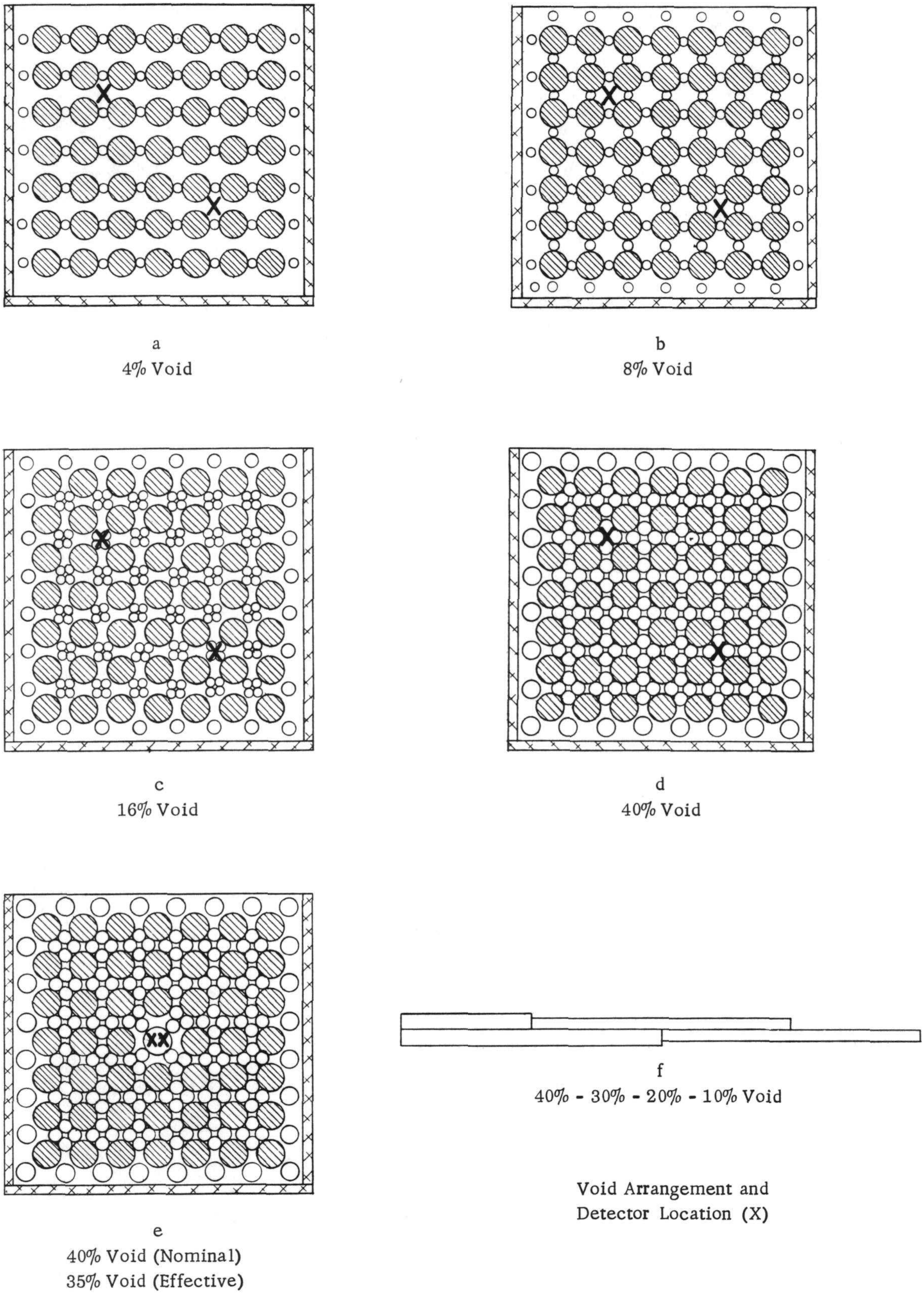

Fig. 8. Void Arrangement and Detector Location

D. Flux-flattening Experiments

A limited number of runs were made to investigate the power distribution across the subassembly. In addition to the normal loading of forty-nine, 4.95% enriched U^{235} rods, radial plots were made with a boron-loaded rod in a corner position, a water-filled aluminum rod at the center, and a ring of eight 9.9% U^{235} rods surrounding the center rod. Figure 9 shows the configuration of the special rods for these runs.

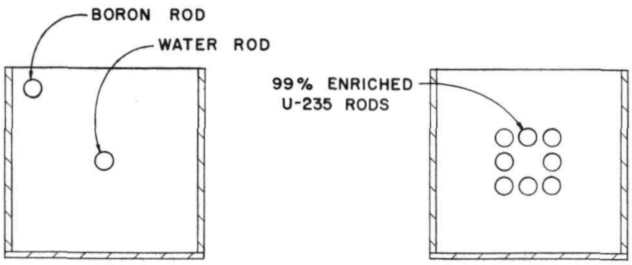

Fig. 9

Configuration for Flux Flattening Measurements

V. EXPERIMENTAL RESULTS

A. Axial Traverses

The raw data obtained on the axial traverse as plotted on a semi-log graph are presented in Figs. 10-17. The best exponential fit to the data gave an e-folding length of 17.9 cm for the assembly. Within the accuracy of the experiment, the slope was considered constant for all of the axial traverses except for the nonequilibrium section at the interface between void regions.

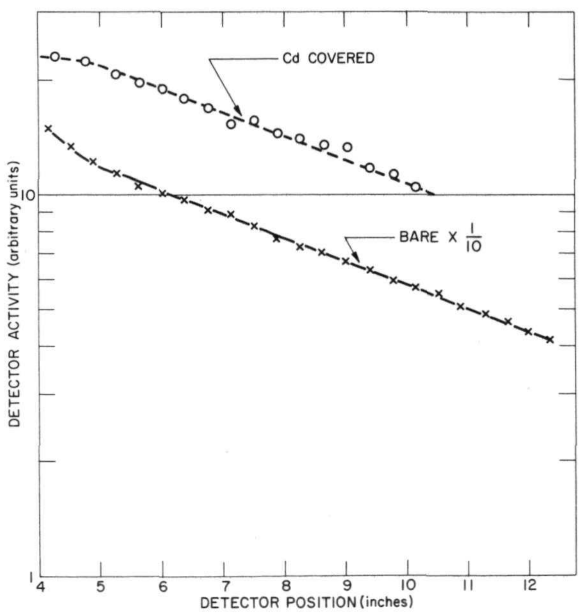

Fig. 10. Axial Traverse - 0% Void

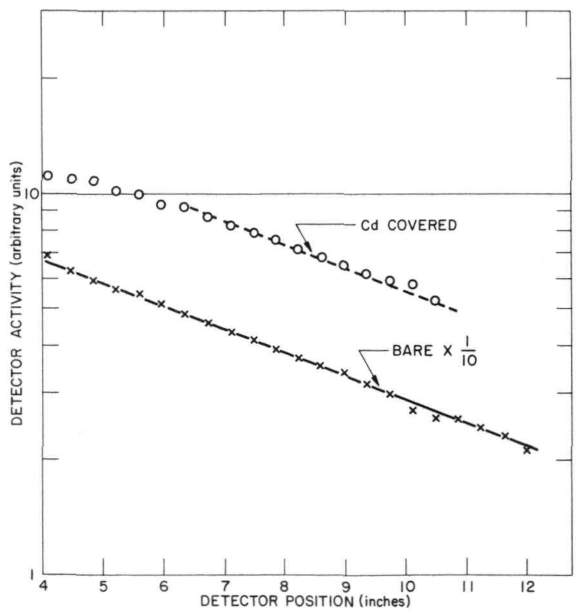

Fig. 11. Axial Traverse - 4% Void

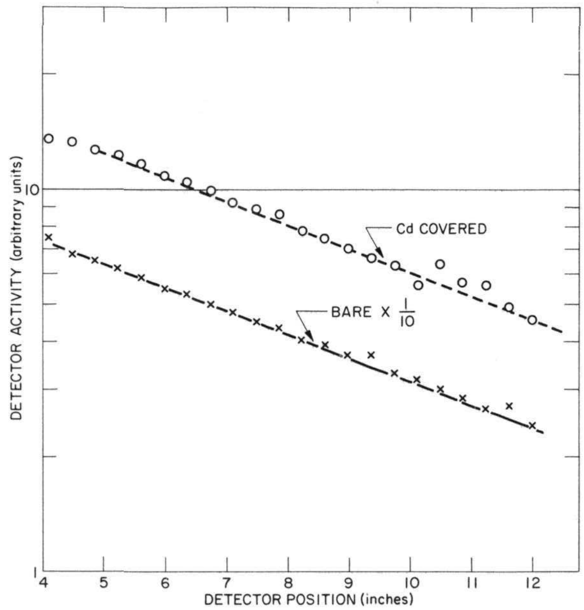

Fig. 12. Axial Traverse - 8% Void

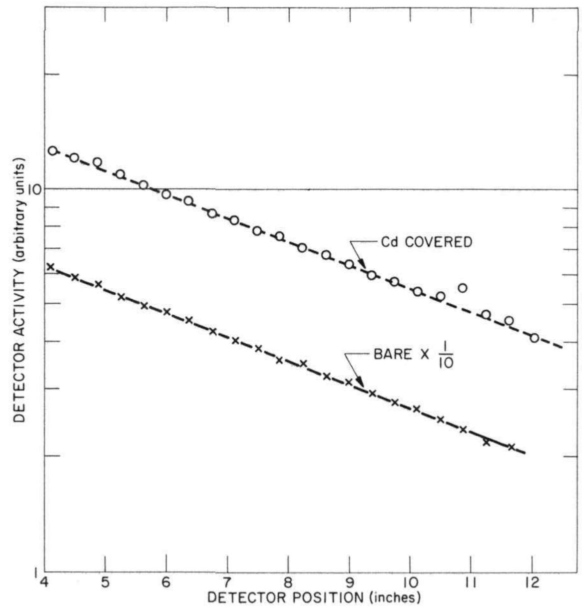

Fig. 13. Axial Traverse - 16% Void

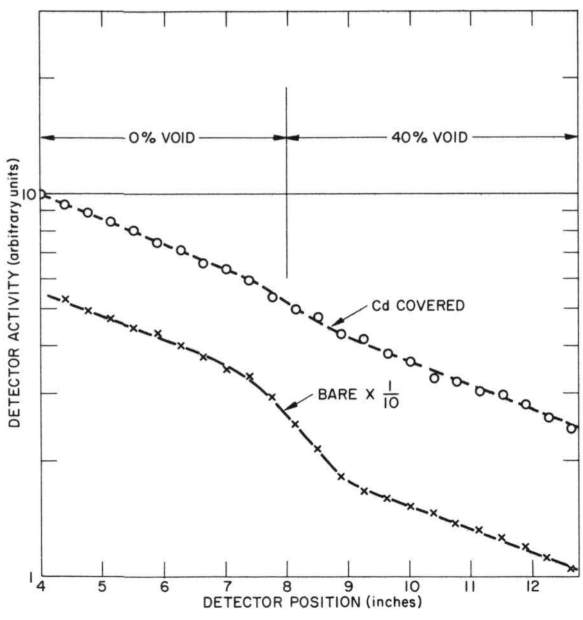

Fig. 14. Axial Traverse - 0 and 40% Void

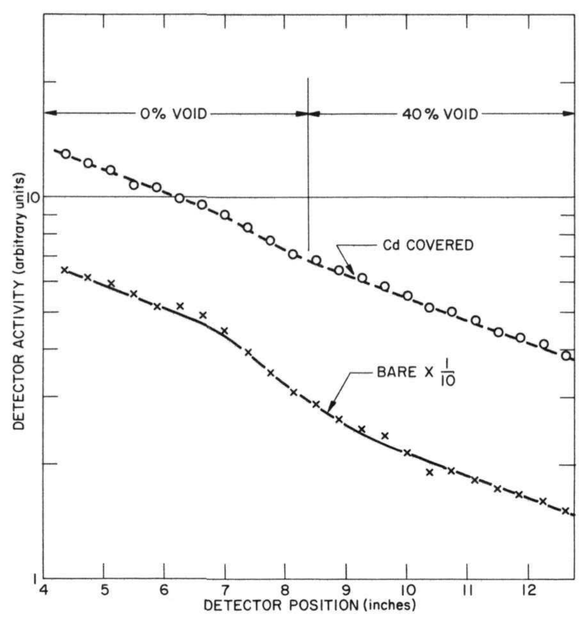

Fig. 15. Axial Traverse - 0 and 40% Void Measured at Assembly Center (35% Effective)

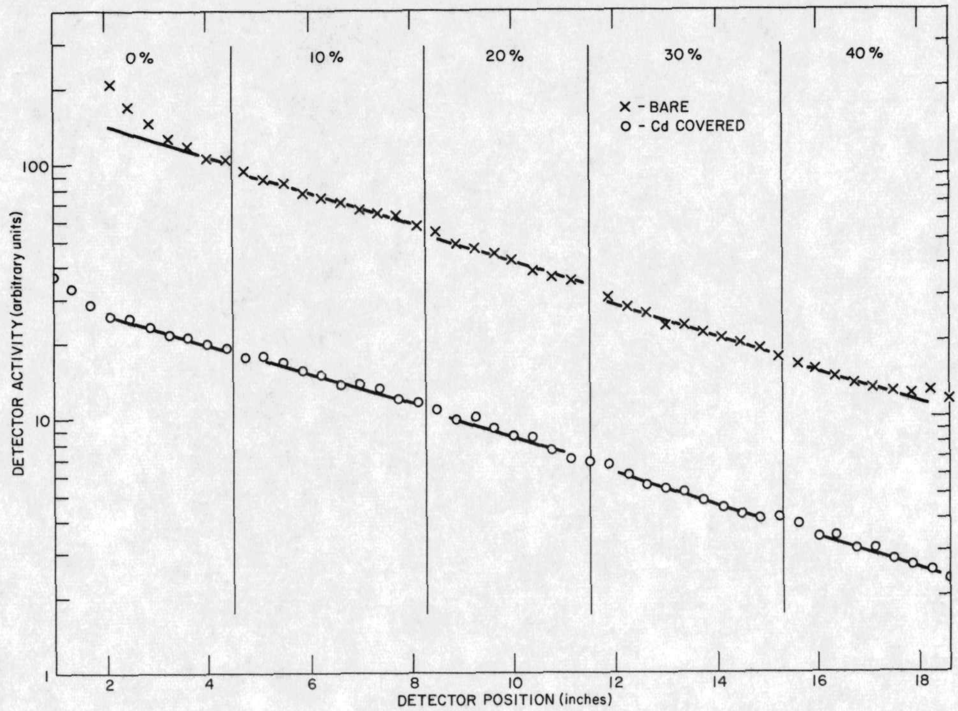

Fig. 16. Axial Traverse - 0, 10, 20, 30, and 40% Void

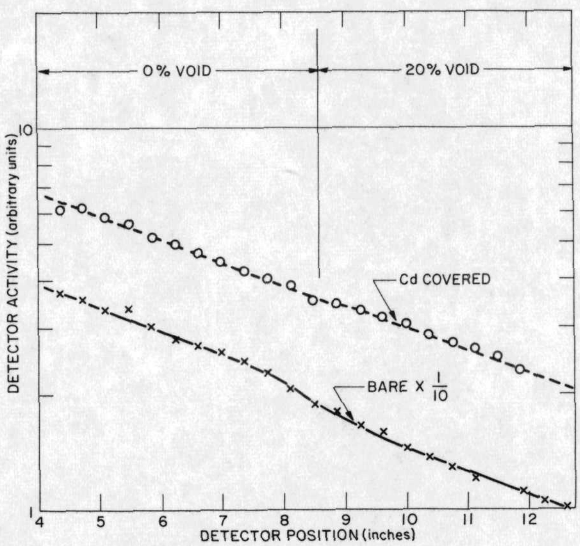

Fig. 17. Axial Traverse - 0, 20% Void with Water Rod at Center

The cadmium ratios were calculated by dividing the count rate for the bare detectors by the count rate of the cadmium-covered detector at the same axial position and multiplying by a factor which adjusted for the difference in sensitivity of the counting equipment. This factor of 1.08-1.12 was determined independently for each run.

The calculated cadmium ratio and description of the runs are presented in Table III. All of the runs, with the exception of No. 6, were in standard detector positions as given by the crosses in Fig. 8a through 8d. Run No. 6 was at the central fuel position (see Fig. 8e).

B. Radial Traverses

The results of two of the radial flux traverses across the diagonal are given in Figs. 18 and 19. It can be seen that the epithermal flux is nearly flat across a subassembly, whereas the thermal flux shows a considerable gradient, peaking strongly in the outer water channels. Obviously, the cadmium ratio is a strong function of position. For this reason, all but one of the axial traverses were made at the same radial position. The magnitude of the data from the cadmium-covered detector have been corrected to adjust for the differences in the axial position of the bare and cadmium-covered wires. However, the cadmium ratios calculated at the same radial position as given in Table III are about 7% high. This may be accounted for by the increased thickness of stainless steel surrounding the bare detectors during the axial measurements.

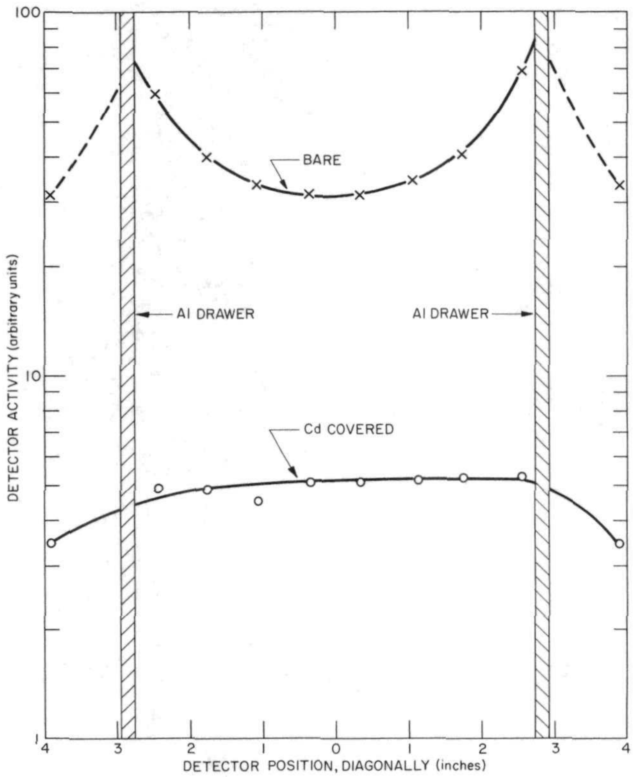

Fig. 18. Radial Traverse - 0% Void

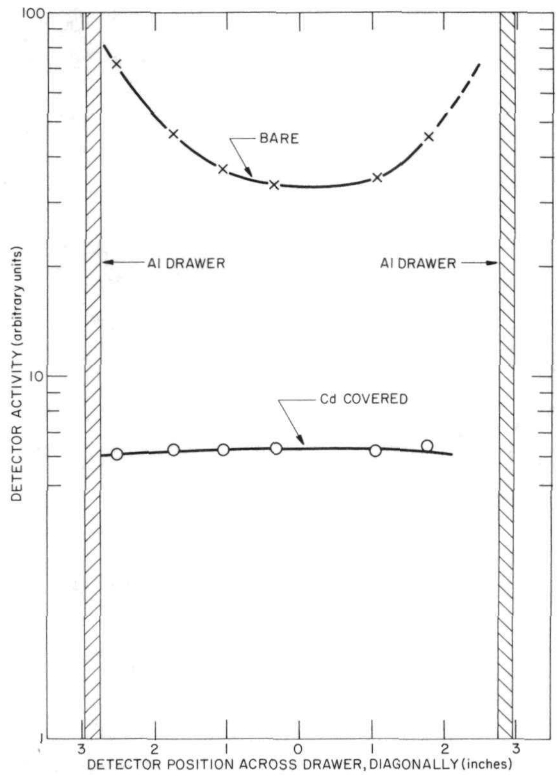

Fig. 19. Radial Traverse - 16% Void

Radial data, obtained with bare detectors only, were also taken for three other configurations. These data included additional detector points across the flats as well as the diagonal. From such data, the ratio of maximum-to-average fission rate in one plane of a single subassembly was calculated. The average fission rate was obtained by assigning a flux value to each of the water channels by means of the measured values for these channels where a detector had been irradiated. By symmetry and interpolation of the measured data, flux values were assigned to the other channels. The fission rate in a given fuel element was then set proportional to the average of the four fluxes assigned to the surrounding water channels multiplied by the fuel enrichment and disadvantage factor (DF). The maximum-to-average fission rate (or power production) was calculated by simple numerical integration:

$$\frac{(FR)_{max}}{(FR)_{ave}} = \frac{(F_{max})\ (DF)(w)}{(1/m)\ \sum_{i=1}^{m}\ F_i\ (DF)_i\ (w)_i} \quad ,$$

where

F is the assigned flux value

DF is the disadvantage factor

w is the enrichment

m is the number of fueled rods.

The values of the DF's used were 1.17 and 1.29 for the 4.95% and 9.9% enrichments, respectively, as quoted in ANL-6302, BORAX V Design and Hazards Summary Report. The results of these ratios under the various assembly conditions are given in Table IV.

Table IV

MAXIMUM-TO-AVERAGE FISSION RATES

Run No.	Void %	Max/Ave	Remarks	Fig. No.
1	0	1.23		
3	8	1.24		8b
4	16	1.25		8c
9	0	1.12	Boron rod in corner, water rod in center*	9a
10	0	1.29	8-9.9% enriched rods in ring around center rod	9b

*Although only one boron rod was used, the ratio was calculated to include the effect of a boron rod at each corner.

C. Cadmium Ratios vs Void Fractions

According to the analysis by Thie et al.,[1] a change in void fractions principally affects the ratio of the epithermal to thermal flux. The ratio of the epithermal (or, more strictly speaking, the epicadmium) flux for the voided and unvoided case is given as (CdR-1) with void/(CdR-1) without void. Following the suggestions of Thie, the calibration of void data is plotted as this ratio vs (1 - void fraction). The result of the eight runs is given in Fig. 20.

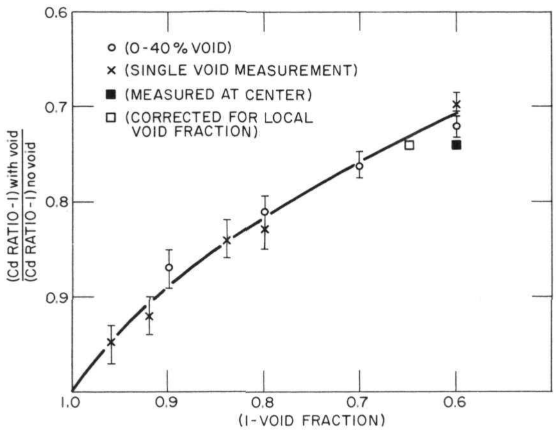

Fig. 20. Cd Ratio vs Void Fraction

It can be seen that the data are consistent within the experimental uncertainty, but that the method does not lend itself to a high degree of accuracy.

Two additional comments should be made with respect to Fig. 20. First, in Run No. 8, in which the cadmium ratio was determined with 20% void and the central fuel position filled with water, even though these factors changed the value of the cadmium ratio, the ratio of (CdR-1) with void/(CdR-1) without void plotted on this graph falls on the curve.

The second comment refers to Run No. 6, which was taken at the central fuel position surrounded with 30% void (see Fig. 8) and is plotted on Fig. 20 as a black square. From Figs. 14 and 17, in which sharp discontinuities were made between voided and unvoided regions, it can be inferred that the effect of the voids on the cadmium ratio is localized to within a region of $\pm\frac{3}{4}$ in. Thus, we would expect from Run No. 6 that the effective void was somewhere between 30% and 40%, instead of 40% as listed on the table. An attempt was made to prorate the void over a $\frac{3}{4}$-in. radius, and a corrected effective void fraction of 35% was obtained, which is plotted as an open square in Fig. 20.

D. Disadvantage Factor

The distribution of fission rate across the diameter of a fuel rod was measured to determine the flux depression and to make an estimate of the disadvantage factor for a fuel rod and moderator cell system. A special fuel rod had been made for the previous critical assembly in ZPR-VII. This rod was modified to allow a $\frac{3}{8}$-in. detector segment to be mounted across the diameter. Additional detector segments were mounted on the surface of the fuel element, and the element mounted in a position so the measurement would be made along one of the assembly diagonals. After irradiation, the wire was accurately snipped into four equal segments for determination of the counting rate per unit weight. By a rough numerical integration across the diameter, the ratio of the average-to-edge flux was calculated to be 0.91.

The flux distribution throughout a water channel was also measured by means of a holder shown in Fig. 7. The ratio of the average flux to the flux at the edge of an element was calculated from these points and found to be 1.07. The disadvantage factor, which may be defined as the ratio of the average flux in the moderator to the average flux in the fuel rod, was then determined in this array to be $\phi m/\phi f = 1.18$. This is in good agreement with a value of 1.19 as given in ANL-6302. In both of these flux determinations the data were insufficient for obtaining any real degree of accuracy, so the result should be taken only as substantiating the calculated disadvantage factor.

VI. ACKNOWLEDGEMENTS

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VII. REFERENCES

1. J. A. Thie, J. Beidelman, and B. Hoglund, Void Measurements in a Boiling Reactor, Nuclear Science and Engineering, 11, 1 (Sept. 1961).

2. R. E. Rice, Editor, Design and Hazards Report Boiling Reactor Experiment V (BORAX V), ANL-6302 (May 1961).

3. G E. Freund et al., Report on the Transient Reactor Test Facility, TREAT, ANL-6034 (June 1960).

VIII. APPENDIX

Calculation of k_{eff}

k_{eff} was calculated for cylindrical fuel arrays of three different radii in order to establish a safe and workable size. Four-group cross sections were obtained by use of the MUFT and SOFOCATE codes. Separate MUFT problems were worked out for each of the three sizes, since the homogenized composition does vary slightly as the radius is changed. The calculated geometrical backing was also given for each size. Number densities, given as input for the cross-section codes, are adjusted with disadvantage factors in the thermal group (SOFOCATE) and with self-shielding in the resonance region (MUFT). These factors were obtained in the same manner as was reported for the reference design.

Figure 21 gives a cross-sectional view of the core and indicates the geometry of the cases considered. The sizes and corresponding k_{eff} obtained by the use of the one-dimensional code, RE-122, are summarized in Table V.

Loading	Radius	No. of Fuel Rods
A	11.4 cm	185
B	13.7 cm	277
C*	15.0 cm	349

*Fuel loading surrounded with cylinder of .020 cadmium.

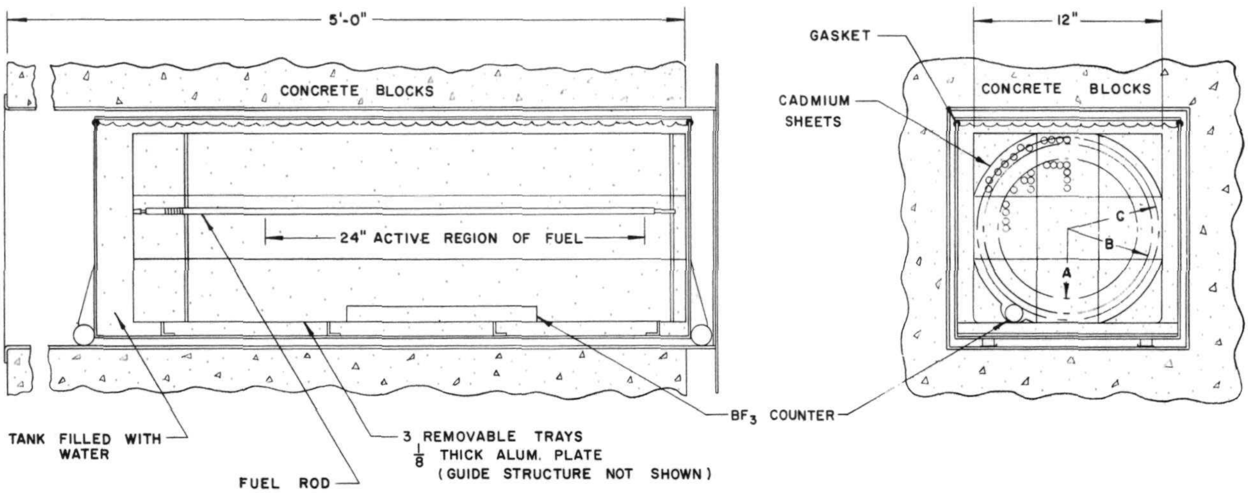

Fig. 21. Axial and Transverse Section through BORAX V Experiment

Table V

SUMMARY OF RE-122 CRITICALITY CALCULATIONS
FOR BORAX V EXPONENTIAL ASSEMBLY

Problem Number	Radius (cm)	Reflector Thickness (cm)	Number of Fuel Rods	k_{eff}
622201	11.4	9.02	185	0.773
2	13.7	6.72	277	0.838
3	15.0	5.42	349	0.857
4 (cadmium clad)	15.0	as for cadmium in thermal group given	349	0.779

The worth of the exponential composition is compared with that of the reference BORAX V all-boiling core in Fig. 22, wherein k_{eff} vs size is given for the two cases. Although the available range for the exponential is restricted, it may be expected that a cycling about the BORAX V reference line should occur, since the composition of the exponential assembly is more accurately depicted (compositional variations occur as the cross regions between mocked-up subassemblies are added with increasing size).

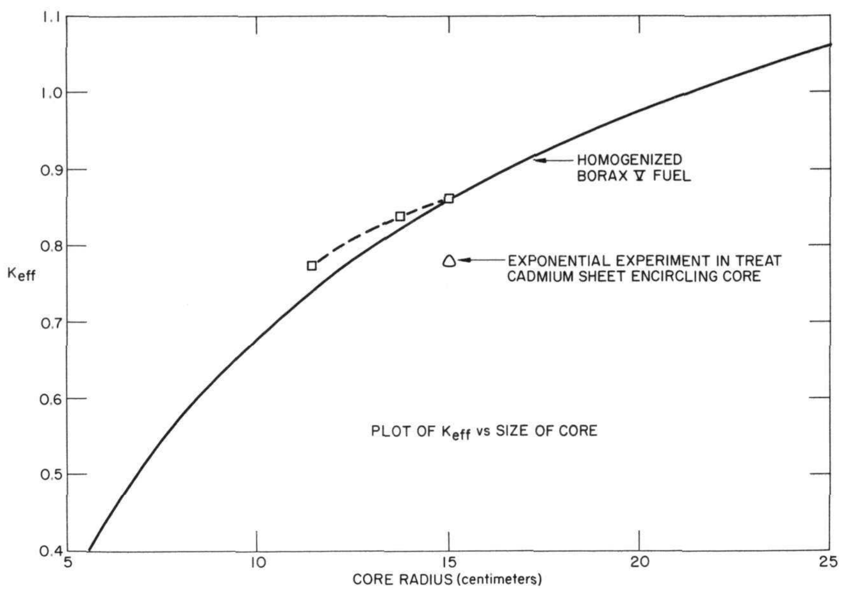

Fig. 22. Reactivity vs Core Size for Exponential (Calculated)

The volume fractions, number densities, and cross sections for the reference design and also for the 349-fuel-rod exponential assembly are compared in Table VI. Homogenization of the control rod followers and other structural aluminum in the reference design lead to a slightly different composition than achieved in the exponential.

Table VI

NUCLEAR DATA, BORAX V EXPONENTIAL EXPERIMENT
(15-cm Radius Core Material, Volume Fractions)

Material	Exponential	BORAX V Ref. Design Cold Boiler
H_2O	0.5979	0.5071
Al	0.05031	0.2222
Type 304 SS	0.05404	0.04159
UO_2	0.2978	0.2292

NUMBER DENSITIES (Adjusted for SOFOCATE Input)

Element	Exponential*	BORAX V Ref. Design(2) Cold Boiler*
H	4.218 (-2)	3.545 (-2)
O	3.326 (-2)	2.671 (-2)
Fe	2.974 (-3)	2.237 (-3)
Ni	3.909 (-4)	4.232 (-4)
Al	3.326 (-3)	1.385 (-2)
Cd	8.496 (-4)	5.751 (-4)
U^{235}	3.037 (-4)	2.277 (-4)
U^{238}	5.779 (-3)	4.625 (-3)

*The numbers in parentheses indicate the powers of 10 by which the tabulated values are to be multiplied to give nuclei/(barn)(cm).

FOUR-GROUP CORE CROSS SECTIONS FOR THE
BORAX V EXPONENTIAL AND
COMPARATIVE BORAX V REFERENCE VALUES

		D	Σ_a	Σ_r	$\nu\Sigma_f$
Group 1	Exp.	2.2403	0.004689	0.09102	0.00835
(10 Mev - 0.821 Mev)	ref.	2.3835	0.0037	0.0776	0.0063
Group 2	Exp.	0.9913	0.002716	0.08795	0.00137
(0.821 Mev - 5.53 kev)	ref.	1.0557	0.0021	0.0765	0.0011
Group 3	Exp.	0.6555	0.02489	0.007725	0.01663
(5.53 kev - 0.625 ev)	ref.	0.7681	0.0193	0.0681	0.0127
Group 4	Exp.	0.2747	0.1607		0.2760
(Below 0.625 ev)	ref.	0.3224	0.1259		0.2115